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AGARD ADVISORY REPORT 278

Flight Mechanics Panel Working Group 16 on

Aircraft and Sub-system Certification by Piloted Simulation

(Homologation des Aéronefs et de leurs Sous-Systèmes par la Simulation Pilotée)

This Advisory Report has been prepared at the request of the Flight Mechanics Panel of AGARD.

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Published September 1994

Distribution and Availability on Back Cover

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Published September 1994

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ISBN 92-835-0757-6

Printed by Specialised Printing Services Limited
40 Chigwell Lane, Loughton, Essex IG10 3TZ

Preface

There is a steadily increasing tendency to use piloted flight simulators for official clearance of selected areas of flight envelopes and of system behaviour or malfunctions. This is a natural and desirable evolution from the wide use of simulation during the development of new aircraft. However there is a lack of guidance for certification authorities and aircraft manufacturers on simulation standards, validation procedures and general information on the advantages and disadvantages of using simulation as part of a clearance programme. This could lead to either inappropriate use of simulators, or unnecessary (and costly) reluctance to use simulation when it is appropriate. In particular, there is concern by many involved with research and engineering development simulators that subjective pilot opinion is often the primary criterion for acceptance of simulators for certification activities. Training simulators are frequently 'adjusted' to improve pilot acceptance for that role, and this can be justified by direct comparison with the aircraft. However, clearance demonstrations on a simulator will not usually be experienced in flight until an operational pilot encounters the conditions or configurations of the clearance. Thus validation of the simulator for clearance tasks must involve rigorous model and simulation system validation as well as pilot subjective tests. Subjective adjustments are unacceptable.

AGARD is able to bring together experts from NATO countries into Working Groups to address issues of common interest. Working Group 16 was formed by the Flight Mechanics Panel at the end of 1987 to produce this Advisory Report. The aim was to provide advice and guidance to Certification and Acceptance Authorities, and Aircraft Manufacturers on the appropriate use of piloted simulation as the sole demonstration for aircraft and system flight clearances.

The Group included members from Canada, Germany, Italy, Netherlands, United Kingdom and the United States. Government R&D establishments, Armed Service R&D establishments and aircraft and simulator manufacturers were all represented. Contributions to this report were provided by all members of the Working Group, who also provided valuable assistance to the Chairman in the editing process.

Alan A Woodfield
Chairman FMP WG-16
Member, Flight Mechanics Panel

Préface

Il existe une tendance, de plus en plus marquée, d'utiliser les simulateurs de vol pilotés pour l'homologation de certaines parties du domaine de vol et du comportement des systèmes en cas de mauvais fonctionnement. En fait, il s'agit d'une évolution naturelle et souhaitable vers l'utilisation généralisée de la simulation aux fins du développement des nouveaux aéronefs.

Cependant, les services officiels chargés de la certification et les avionneurs ne disposent pas de suffisamment de consignes sur les normes de simulation, les procédures de validation et les avantages et désavantages en général de l'emploi de la simulation dans le cadre d'un programme d'homologation. Cette situation pourrait conduire soit à une utilisation inappropriée des simulateurs, soit à une certaine résistance inutile (et coûteuse) à l'emploi de la simulation là, où elle est nécessaire. En particulier, beaucoup de ceux qui sont impliqués dans le développement des simulateurs de conception et de recherche se disent préoccupés par le fait que l'avis subjectif du pilote est souvent le critère d'acceptation principal d'un simulateur dans le cadre de la certification.

Les simulateurs d'entraînement sont souvent "ajustés" afin de faciliter leur acceptation dans cette mission par le pilote, ce qui s'avère justifiée lorsque la comparaison est faite avec un avion en vol. Cependant, les démonstrations pour certifications sur simulateur ne sont normalement vérifiées par le pilote opérationnel qu'au moment où il rencontre en vol les conditions ou les configurations de cette même certification. Il s'ensuit que la validation des simulateurs pour des tâches de simulation passe nécessairement par la certification rigoureuse des systèmes de modélisation et de simulation, ainsi que par les tests subjectifs des pilotes. Les ajustements subjectifs sont inacceptables.

L'AGARD a la capacité de réunir des spécialistes des pays membres de l'OTAN dans le cadre d'un groupe de travail pour examiner des questions d'intérêt mutuel. Le groupe de travail No. 16 a été créé par le Panel de la Mécanique du Vol à la fin de l'année 1987 avec pour mandat l'élaboration du présent rapport consultatif. Le groupe s'est donné comme objectif de fournir des conseils et de formuler des orientations concernant l'utilisation appropriée de la simulation pilotée en tant que moyen unique de démonstration en vue de l'homologation des aéronefs tant du point de vue de leurs performances de vol que de leurs systèmes, aux autorités responsables de la certification et de la réception des aéronefs, ainsi qu'aux fabricants des simulateurs et aux avionneurs.

Le groupe a été composé de représentants du Canada, de l'Allemagne, de l'Italie, des Pays Bas, du Royaume-Uni et des Etats-Unis appartenant à des établissements de recherche et développement gouvernementaux et militaires, ainsi que de représentants d'avionneurs et de fabricants de simulateurs.

Des contributions au présent rapport ont été fournies par tous les membres du groupe, qui ont en outre bien voulu prêter leur concours précieux au président lors de sa rédaction. Des contributions à ce rapport ont été fournies par l'ensemble des membres du Groupe de Travail, qui ont également prêté de l'aide au Président lors de la phase de relecture du document définitif.

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1 INTRODUCTION

Piloted flight simulators are a powerful tool for designers to study the influence of the pilot in the dynamic behaviour of new aircraft, new systems and new operating environments. They also provide training for pilots in managing the complex cockpit environment and the wide range of emergency conditions which might arise from failures or adverse operational conditions. For many years simulators have been used successfully to predict and assess solutions to problems arising during the development of new aircraft and systems. However, until recently, with the exception of very specialised aircraft such as the US Space Shuttle, all aircraft acceptance/certification has required flight test demonstration.

This situation is changing as the complexity of safety critical systems increases and presents the acceptance authority with a very large set of potential failure modes. Also, improvements in the standards of flight simulation are increasing confidence in their ability to represent many flight situations well enough to limit the range of conditions that require flight testing. By holding flight clearance testing within reasonable bounds there are significant savings in cost and time, which are eagerly embraced by both manufacturer and customer. There are now examples where piloted simulation has been used to 'demonstrate' to acceptance authorities a range of failure modes of, for example, a multi-channel 'fly-by-wire' flight control system. From these demonstrations, the authorities, quite reasonably, selected for flight demonstration those situations that appeared to be most demanding and most probable. Economic and practical time limitations are going to increase the range of situations where piloted simulation will be used as a direct part of the acceptance and certification processes for military and civil aircraft and their systems.

This increasing use of piloted simulation for acceptance testing of aircraft is a natural consequence of the increasing physical understanding of aircraft and their operational environment, and confidence in the 'validity' of piloted simulation. Confidence in validity is the criterion that must be applied. How is such confidence derived?

In the above case of multi-channel 'fly-by-wire' systems, confidence was obtained primarily from the subjective comments of experienced pilots involved in development flight testing of the aircraft. This is an important and necessary element of validation. Is it sufficient? The wide experience of members of the Working Group is that pilots' subjective comments are not sufficient on their own to justify confidence in the validity of a simulation. For example, it is not unusual in developing training simulators to try to compensate for physical cueing deficiencies, or computing delays, by altering the aircraft model to make the simulator appear to be more "like the aircraft" than the earlier version with the more representative aircraft model. This method of compensating for cueing deficiencies is possibly acceptable for a training simulator, where the responses can be tuned to be a satisfactory representation of specific training tasks that are demonstrated on the aircraft. (Although even with training simulation there can be problems when users subsequently modify the training syllabus to use a wider operational envelope.)

For acceptance test purposes, however, it is not acceptable to alter aircraft/system models to compensate for cueing deficiencies. Although this can gain pilot acceptance and confidence in the areas which he has experienced in flight, there can be little confidence that the simulator is presenting adequately those vital situations which will not be demonstrated in flight. Further, the use of such model compensation can be highly misleading because pilots and engineers from both the manufacturer and the acceptance authorities can be led to a false sense of confidence, and the simulation engineer can believe that the simulation is valid in general. All parties need to ask the questions:

a For what sets of conditions has validity been confirmed from flight test?

b What confidence can be placed in simulation of conditions outside the validated range?

The art of optimising a simulation to maximise its validity for specific tasks depends on a wide range of factors, including the physical characteristics of available cueing systems (visuals, motion, sound, control loading, g-seats, etc.), computing systems (architecture, speed, capacity, etc.), and aircraft category. Most cueing systems, with the important exceptions of visuals and motion, have only small delays. Visual scene generation often takes several computing cycles and the drive algorithms may contain rate and acceleration terms to try and compensate for the delays, which are typically between 70 and 140 milliseconds. Such compensation must be used with care as it is easy to overcompensate and introduce unnatural overshooting of the correct visual scene following energetic manoeuvres. Motion drive algorithms are complex and contain both scaling and dynamic response filters designed to generate representative aircraft movement cues over a limited bandwidth of frequencies that are compatible with the acceleration, velocity and movement limits of the motion system. Thus acceptance authorities and manufacturers need to justify confidence in simulation results from either relevant flight test validation or from an identification and acceptance of the validity of the simulation system design methods applied to the specific simulator. Pilot acceptance is not sufficient, although it will always be one of the necessary conditions.

This Advisory Report collects the views and experience of international experts in flight simulation, and seeks to inform manufacturers and acceptance authorities of past experience with the use of simulation in both development and acceptance/certification testing. It discusses a wide range of practical issues arising in modelling, providing cues, and integrating aircraft and simulation systems. It introduces guidance on validation methods, outlines issues which may need to be considered by acceptance authorities, and considers areas where simulation is likely to be a major contributor in acceptance testing. The main body of the report is devoted to simulator validation: the factors involved, and the techniques which are available. In the Appendices, specific examples are given of the use of flight simulation for certification and customer acceptance of both military and civil aircraft. These, and more recent examples, all confirm the general conclusions of this report.

2 CURRENT USE OF SIMULATION FOR CERTIFICATION/ACCEPTANCE

2.1 Civil Certification Experience

The use of piloted simulation by the aircraft manufacturer in the design and development of new civil transport aircraft is very extensive. No aircraft manufacturer today would undertake the launching of a new aircraft programme without major usage of simulation. First, sophisticated computer models will be used in a proof of concept, to predict the aeroplane's stability margins, estimate performance characteristics and analyse handling qualities and failure mode effects. Second, piloted simulations will be developed from these models and used to evaluate manoeuvres, procedures and systems before they are cleared on the aircraft and to provide a confidence factor for the aeroplane's certification. The areas of application range from pure system development, with and without prototype hardware in the loop, through crew workload studies in normal, abnormal and emergency procedures, to the assessment of handling qualities in all flight phases for specific control law design.

However, compared to the extensive use of simulation in aircraft design, the direct application of simulation in certification tests is currently still limited to the assessment of (sub)systems failure cases that are very difficult to obtain in-flight. The simulator has proved to be particularly suited for that purpose because it provides time to analyse the warnings and procedures, to reproduce the tests as many times as is required, and to cover a wider spectrum of flight conditions. In addition it avoids exposing people's lives and aircraft to conditions of potentially high risks, and it is possible to create failure cases in controlled meteorological conditions that are otherwise difficult or impossible to obtain to order from the natural environment (e.g. turbulence, wind shear, etc.). Finally, it helps the manufacturer to define the certification flight programme proposed to the certifying authorities.

No specific rules exist by which authorities accept that proof of compliance with a certain requirement can be given by simulation. Further, Airworthiness Requirements[1] do not dictate the acceptable means of compliance (analysis, ground or flight test with the actual aircraft or flight simulation) and leave the choice to the manufacturer. The aircraft manufacturer always takes the lead in proposing the means for proof of compliance with a certain certification requirement. The decision to propose simulation or flight test is governed by economics, taking into account all factors that are expected to be of influence. These may be expense, available time, risks involved, availability of equipment and human resources, probability of success, anticipated attitude of airworthiness authorities etc. The final division between actual flight testing and alternative means is the result of negotiations between the authority and the manufacturer and, amongst other factors, is dependent on the availability of "proper" flight testing and simulation facilities.

Current practice is for compliance with airworthiness regulations in normal aircraft operation to be demonstrated in flight test. Failure cases with major consequences and with a probability $< 10^{-7}$ will require either flight or simulator tests. The type of test is at the discretion of the airworthiness authorities. Other failures with hazardous consequences or with a probability $\geq 10^{-7}$ are assessed in simulator tests. Performance of most avionic systems and failure cases are usually certificated in the simulator with some flight tests to validate the simulator results.

However, if the Authorities suspect that the effect of a failure on flight crew workload and/or ease of information interpretation is influenced by the validity of the simulation, they will always require in-flight verification regardless of the results of the simulator tests. This happens for instance when a new aircraft has very novel and unusual features, in which case flight tests may be required even for very rare failures.

An important function of simulation regarding airworthiness certification is that before or even without actually flying, the certification pilots can get confident with the control and display systems and study specific flight control and instrumentation design issues in a wide spectrum of flight conditions, before being subjected to the additional workload of a real flight. When the complexity of a system increases significantly, as with integrated EFIS, automated flight control and central warning systems, the need to have the total picture in a real aircraft environment during tests increases accordingly. The simulator is then very helpful in evaluating the system features and pinpointing the bottle-necks as a preparation for the actual flight tests (e.g. to demonstrate effects of new software versions of certain systems).

In most cases the simulation facility offered will have some limitations compared to the aircraft or prototype because the aerodynamic data are not yet fully known, or because the simulator has limitations in vision, motion or control capabilities, or because actual flight hardware is not available. As for training simulators, the manufacturers have, on request, to provide the certifying authorities with objective information concerning the validity of the simulation for the proposed task. A final decision to accept that the simulation is suitable for the proposed task is made only after a subjective simulation assessment by a certification pilot. An important aspect in this decision process is whether the quality of the simulation is such that the simulation results can be considered as conservative. If the difficulty of the piloting task is increased slightly in simulation with respect to real flight this would normally be more acceptable than a corresponding reduction in difficulty. However, it is no longer safe to assume, as was frequently true in the past, that flying a simulator will be more difficult than the aircraft. The introduction of active flight control systems has produced several instances where a simulator has been easier to fly than the aircraft. Experience shows that, when in the course of a simulation programme the confidence of the certification team in the simulation facilities and the test proposals of the manufacturer increases, the amount of in-flight validation required will decrease. Since currently this varies from country to country, and within a country from aircraft to aircraft, it may be that it will be difficult to draw up a general set of rules for accepting that simulation is applicable. However, with the advent of a Joint Airworthiness Authority in Europe, with teams of experts handling the same part of the certification process for all aircraft offered for certification, it may very well be possible and even necessary that general rules will emerge in the future. Guidance on crucial issues will be necessary until that time.

Valuable experience in civil airworthiness certification was gained during the certification programmes of the Fokker 50 and Fokker 100, and in the joint European Airworthiness certification programmes of the Airbus A-320 and the Boeing 747-400 aircraft. For a significant number of aircraft sub-systems, the authorities have already accepted that flight simulation programmes can contribute in providing proof of compliance with airworthiness requirements. Appendix A presents a number of specific examples.

During the A320 development programme (Appendix A), the simulator played a very significant role in predicting accurately the response of the aircraft under various testing configurations. However, two specific flight handling characteristics were found to be lacking in realism on the simulator.

i. In studying the behaviour of the aircraft at aft CG limits in the "direct control law" mode, the simulator was found to be more demanding to fly than the aircraft. This was attributed to the following factors:

    a) The simulator had no motion system.

    b) At time of test, the latest aerodynamic data were not used. It was concluded that small differences in longitudinal stability margins at aft CG can cause significant variations in handling qualities. (Even after updating the aerodynamic model, it was found that pilot inputs in the simulator tended to be larger than those used in flight, and the simulator handling task was more demanding than on the aircraft. However, the simulator response characteristics with the system stabilisation in the augmented mode, was representative of the aircraft.)

ii. Some early versions of the control laws were evaluated as satisfactory on the simulator during the landing and flare phases of flight. However, these were found to be unacceptable on the aircraft during flight in significant gust or cross-wind conditions. This was attributed to the lower level of pilot stress experienced on the simulator and the absence of a motion system. The real aircraft had to be used extensively to refine the longitudinal control laws to obtain the desired flare characteristics during various weather conditions.

2.2 Military Acceptance Experience

Flight simulation is more widely used to support the acceptance of military aircraft than in the certification of civil aircraft. The flexibility of operation which characterises military aircraft usage means that the flight testing required, both for aircraft development and for aircraft clearance, is far more extensive than that required for the equivalent clearances on civil aircraft. As well as operating over a much wider flight envelope, the configuration of military aircraft vary with the carriage of external stores, adding to the number of cases which must be flown.

New military aircraft are designed and constructed as a result of protracted discussions between Industry, Government Departments, Armed Forces, and Agencies responsible for procurement. Although export appeal will have some influence on the decision to proceed, National requirements prevail. In the case of a new civil aircraft, commercial pressures dominate, and the manufacturer will design an aircraft with world-wide appeal and with an eye to International Certification. Consequently, the procedures for design, test, and acceptance of military aircraft show a much greater variation between countries than those relating to civil aircraft. In the United States the procedures are contained in Mil Standards, in the UK in Defence Standard 00-970, and so on. For multi-national programmes, the procuring authority which represents the participating nations will formulate new requirements based on individual national requirements. Consequently, the basis for military aircraft acceptance does not share common ground to anything like the extent to be seen in the certification of civil aircraft.

At the same time, the various national requirements for military aircraft acknowledge, to a greater extent than the civil requirements, the need for the use of simulation to support the acceptance process. Section 5.2 expands on this theme. It is a reflection of the extensive, and sometimes hazardous, nature of the test flying which is involved. The aircraft must be cleared to extreme points of the flight envelope in a wide range of loading conditions, weights, and store configurations. Rapid rolling and spinning tests require particular care. Testing special equipment, such as radar, stores management, and weapon delivery systems, are demanding on flight time, and call for facilities such as low-flying areas, ranges, and ground and air targets.

The common factor between military and civil practice in the use of simulation for acceptance and certification is that the agreement to do such testing has to be approved by the certifying authority. Each case is discussed on its merits, depending on precedent, the available standard of simulator, and goodwill on both sides. The benefits are widely recognised, including the opportunities that the simulators give for pilot familiarisation and their ability to represent conditions such as turbulence which are rarely available exactly when required in flight.

Appendix B contains a number of examples of flight simulation activities which have helped in the clearance of recent military aircraft. They illustrate the wide diversity of problems which have been cleared by simulation, on many types of aircraft. They cover a wide range of specialities such as flying qualities, flight control, avionics, stalling and spinning, ground handling, terrain following, weapon aiming and failures. The examples of Appendix B are just those instances of clearance work known to members of the Working Group. Most military aircraft entering service in the past twenty years have benefited from simulator tests in support of flight clearance. The advent of new types of aircraft, such as the X-31 and the forward swept wing X-29 before it, will increase the need to predict aircraft and flight control performance prior to first flight. Simulators can take some of the risk out of flight tests if the laws of motion and aerodynamics are accurately applied. The use of simulators to support aircraft development and certification will inevitably increase with the increasing development costs of military aircraft and their correspondingly higher cost per flight hour.

3 VALIDATION ISSUES

This section "sets the scene" for the process of validation. The implications of decisions taken during development of the simulation are discussed, and a number of potential problem areas are identified. In many instances, the issues which arise have a bearing not just on validation, but indeed on the very feasibility and practicality of the use of simulation in the certification/acceptance process. It is convenient to address these aspects briefly here. Advice on specific methods of carrying out validation is covered in Section 4.

Before proceeding further it is important to provide a definition of validity in this context of piloted simulation. The definition used here is:

> A piloted simulation will be valid for a selected task when the representation by individual components of the simulation and by the complete simulation meets both the quantitative requirements of the manufacturer/authority and the subjective evaluation of pilots with relevant experience such that a manufacturer will confidently present simulation as the sole means of demonstrating compliance with the Authority's certification or acceptance requirements for some element of that task.

Before proceeding it is also appropriate to define the term 'verification'. This is used here for the more specific action of objectively comparing the response of a component of simulation with its specification, e.g. is the implementation of a mathematical model a correct representation of the specified model. Verification is usually a precise objective comparison, whereas validation contains both verification and subjective assessments to evaluate the fitness of the system for the required purpose.

Validation covers all aspects of the complete simulation as shown in Fig 1 - the mathematical model of the vehicle, methods used to represent on-board systems and equipment, the atmospheric and operational environment to be represented, the software needed to create all these components, and, most important in this context, the ways in which these systems interface with a the pilot. Issues relating to the interactions between pilots and flight simulators are probably the most complex and contentious and these are considered first. Each of the other aspects is then considered in turn in the sub-sections below.

3.1 Pilot Interaction

Piloted simulation will be appropriate for situations and configurations where acceptance depends on

a pilot's dynamic response behaviour (handling qualities, workload and control activity)

b piloting procedures, particularly under high stress (trained procedures)

c complex situation monitoring near the boundaries of safe flight (safety margins).

(These are exactly the same requirements that apply for selecting flight acceptance tests as the involvement of aircrew is a common feature to both flight test and piloted simulation.)

The validity of results from a simulation depend directly on its capabilities to stimulate the same task performance, subjective opinion of handling qualities and workload, and control activity from a pilot as would be found in the aircraft for the chosen tasks.

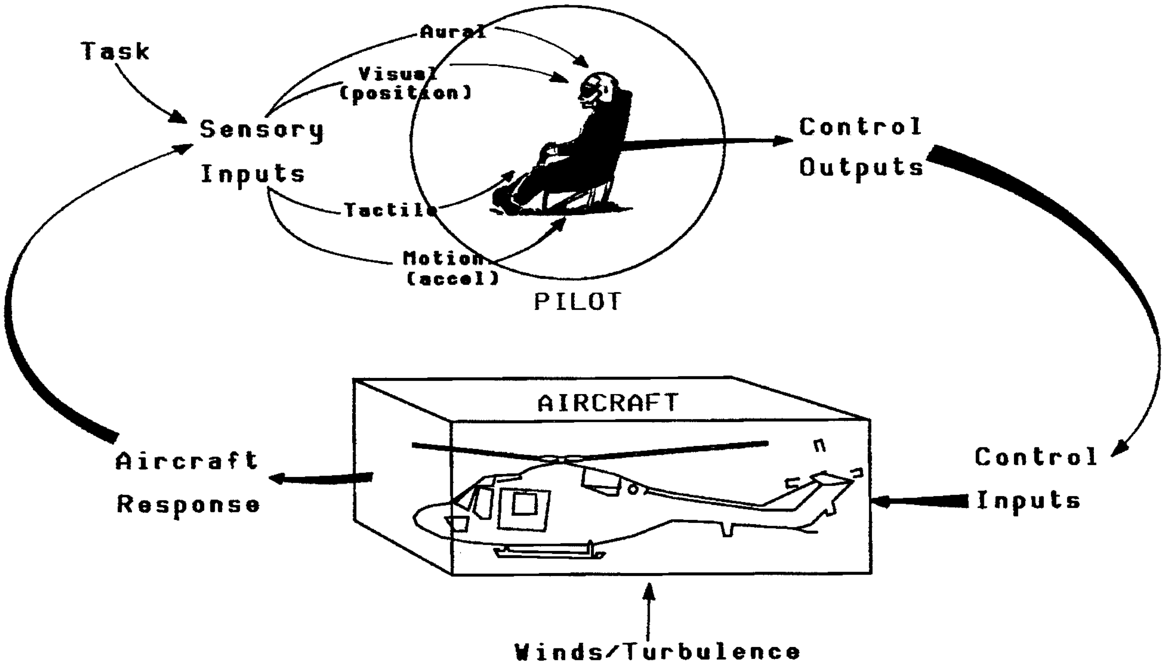

Fig 1: Piloted Simulation System

It is important to put 'validity' and 'realism' into proper perspective as they are not equivalent. Although striving for 'realism' will improve the general quality of a simulation, it is in the end an unachievable goal. Simulators will always differ from flight in various ways and to greater or lesser degrees. One example is the simple flight manoeuvre of changing from straight flight to a steady turn. No ground based simulator can ever produce correctly both the acceleration transients when setting up the turn and the steady 'g' load in the turn. Degrees of realism are ill-defined and increased realism will only enhance validity if it is applied to simulation features which directly affect the chosen tasks, e.g. improving the detail of airport buildings will not improve the validity of a simulator in its response to wind shear. **Validity depends on establishing a high level of confidence that pilot responses and performance in the simulator will be the same as in the aircraft for the chosen tasks.**

This section addresses issues that affect pilot responses and for convenience separates these into handling and situation awareness activities. A summary of pilots dynamic behaviour is followed by discussions on dynamic cueing systems. Situation cueing systems are followed by a sub-section on pilot adaptability, stress and factors affecting the pilot's subjective assessment of the simulator. Always remembering that, although pilot subjective assessment of validity is not sufficient on its own, no simulator will be accepted as valid unless pilot opinion is favourable.

3.1.1 *Pilot dynamic sensing and response*

People have a wide variety of sensors with which they identify what is happening to them and their immediate world. These sensors often provide signal redundancy and processing of signals is a complex activity including learned responses. Some of the apparent inconsistencies in pilot assessments of simulation arise from their adaptability (ability to learn). Others are often associated with the fact that some sensors contribute to an overall sense of situation without giving a precise quantitative measurement, e.g. motion sensors of the inner ear are imprecise on their own but provide good control when combined with limb position sensing and even better control when vision is added. This does not mean that the inner ear sensors are not vital, as is clear from the distress and difficulties in balancing caused when they are damaged, but it does mean that pilots may not be aware whether a particular motion cue is or is not present. They will, however, usually identify changes in the behaviour of the vehicle as all motion is turned on or off. However, where motion cues are important for a task, there will be effects on some if not all of the key measures of validity, i.e. task performance, subjective opinion of handling qualities and workload, and control activity. If task performance or subjective opinion are affected then it is not too difficult to assess the effects on validity. If only control activity is changed then pilots may very well have adapted to the behaviour of the simulator without noticing that they are using different control inputs from those that would be used in the aircraft in the same situation.

The whole process of learning to respond to the complex mixture of sensory inputs experienced in flying, or even ordinary daily activities, is only partly understood. People are able to adapt quite rapidly to sensory deprivation of many different kinds. Quite often task performance is unaffected; sometimes they will have to work harder to achieve this performance, whereas at other times they find a different way of achieving the same result. However, this different way may be inappropriate in the full sensory environment.

The stronger senses of vision, touch, hearing and smell/taste will dominate any appreciation of situation, but confusion may arise if other senses do not agree with the stronger senses. These effects can be subtle, as described above, or more obvious, e.g. the difficulty experienced in maintaining balance when viewing large screen action film without any accompanying motion.

In considering pilot dynamic responses it is convenient to consider the person as a complex servo control system including both sensors and actuators, Fig.1, in order to understand the main consequences of differences between motion feedback in flight and on a particular simulator. Any closed loop servo system, e.g. where rate and/or acceleration feedback is used to improve the control of position, can become unstable as the gain, i.e. the amount of input to adjust for a given error in output, is increased, or as the time lead (phase lead) of the feedback decreases. Real acceleration gives more lead than velocity (rate) feedback, which in turn leads position (attitude). Thus removing the acceleration cues provided by motion will reduce the capability of a pilot to stabilise and control the simulated aircraft.

Direct vision of the outside world provides position information. Velocity information can be derived by observing successive positions but this lags rather than leads position. Direct rate information is obtained in peripheral vision but is largely direction of velocity rather than quantitative information. Sensors in the inner ear and muscles respond directly and progressively to velocity and acceleration and these provide stabilising lead in flight. In a simulator there is no natural connection between artificial visual scenes and the behaviour of motion systems. Indeed the limits on total movement in a simulator mean that it is impossible to represent the full relationships between visual and platform motion. Fortunately, human sensing and response frequencies are limited and there are sensory thresholds. These mean that important and relevant stabilising lead can be provided within the limitations of practical simulation motion systems.

The influence of simulation approximations in motion and visual on a pilot's control activity compared with the same situation in flight will depend on the required precision and agility of the task, and also the stability margin at normal pilot gains. If simulation approximations erode the stability margins sufficiently to require a significant change in pilot gain, or even more dramatically to change the overall control strategy, then the simulator is no longer appropriate for flight clearance even though it will often be flyable using different control techniques. Typically pilots will initially modify their control activity, but if this fails they may overcontrol or adopt a form of open loop control using pulse or small step inputs and waiting to see the steady state change. This approach is a valid way of achieving stability as open loop systems cannot be driven unstable (although they may be naturally unstable). These methods of compensating for deficiencies may lead to totally different control strategies compared with those used in flight although they may give similar performance. Pilots will often compare this with playing computer games where dynamic motion feedback is usually missing. In most cases the lower stability margins in a simulator make a given task more difficult than it is in the aircraft. However this will not necessarily be true where pilots change their control strategy. There are also cases where feedback from motion cues make the aircraft difficult to control[2] and this would make a fixed base simulator easier to fly than the aircraft. This latter effect can be particularly significant in advanced flight control aircraft where large control surface movements and complex interactions can be demanded for 'normal' control inputs.

In the following sections the effects of various simulation approximations that influence dynamic behaviour are discussed in relation to a variety of tasks. There are three main topics considered:

a computing time delays and phase lags

b motion feedback

c harmonisation of various cues

3.1.1.1 Computing delays

Computation of vehicle and system states and the visual scene requires time and introduces delays that are not present in flight. Pilots will not usually be able to identify that lags are present unless they become very large, but these delays will reduce the stability margin on any simulator compared with that in flight. Delays will depend on many factors including computing speed, computer configuration, operating system, software configuration, hardware interfacing, etc. It is important to identify actual delays as both the total delays and the relative delays between different cueing systems (see the later section on harmonisation) are important. Current requirements[3] for Civil Training Simulators to meet the highest certification standards are

> '150 milliseconds or less after airplane response', for Visual, Motion and Instrument systems response to an abrupt pilot controller input, or

> 'a transport delay* of '150 milliseconds or less after control movement'

This delay relates to the rather gentle manoeuvres made by civil airliners during take off, cruise and landing. For more agile manoeuvring by military aircraft the maximum acceptable delay will be less than 150ms. Military aircraft specifications[4,5] require delays in aircraft systems of less than 100ms. Many aircraft models will include delays of various kinds already present in the aircraft systems. Control stability is critically dependent on total delay times and this means that the total of aircraft and simulator delays should not be allowed to exceed 100ms by a significant amount. A suitable target would be significantly less than 100ms additional delay from simulation systems. This may prove a difficult task, but it is a worthwhile target if the effects of delays are to be minimised. If the additional delay is greater than 50ms then the effects on piloting strategy and performance must be carefully evaluated. In general the presence of motion cues with delays less than visual cues will reduce the effects of visual system delays.

Because pilots' responses are limited to frequencies below about 2Hz it is possible to simplify aircraft system models, e.g. by eliminating high frequency structural filters, and thereby reduce total time delays or phase lags. These reductions can be used to offset some of the delays and phase lags arising from simulation systems. This technique was used in the NASA Space Shuttle simulation described in Appendix B.

Compensation algorithms are commonly used to alleviate the effects of time delays, particularly in visual scene generation and display systems. Typically these use the current calculated rates of movement to predict a position error at the end of the computation and display process. (It is not desirable to apply filters to position signals alone as the process of differentiation introduces delays in the derived rates which are not present in the directly calculated signals.) Whilst judicial use of such algorithms can produce significant improvements, they can never be more than a simple prediction and can even increase errors following abrupt movements. Time lost through systems delays and lags can only be partially recovered and every effort must be made to minimise such delays. In general the effects of any delays in the response of cueing systems to pilot inputs that are over and above delays inherent in the aircraft should be evaluated even if compensation algorithms are operating.

3.1.1.2 Motion feedback

It is possible to use visual cues to derive rates of movement, or even accelerations. However, this requires differentiation of position information and thus there will always be a small lag relative to the perception of position. In general visual cues of angular positions and rates are more obvious than those for translational position and velocities, unless the aircraft is very close to the ground. Height rate information is particularly difficult to obtain from visual scenes unless the aircraft is hovering close to a vertical object which is rich in detail.

Motion systems provide the pilot with advanced warning about future changes in aircraft motion that is not available from any of his other senses. Sometimes this information can be obtained from cockpit instruments, but this often leads to unrepresentative control strategies, or is not a usable source of information, e.g. when hovering and landing using external visual cues, when there is insufficient time to scan cockpit instruments.

Motion systems can be either the familiar motion platform which moves the entire cockpit, or 'pseudo' motion systems, such as dynamic seats, which act upon parts of the body to induce motion sensations. (Large quasi-steady normal acceleration cueing through 'g' seats and visual effects are part of the cues required for situation awareness and are dealt with in Section 3.1.2)

Currently available platform motion systems can adequately represent abrupt and high frequency motions such as buffet or the consequences of engine failure during take off. The particularly difficult areas are low frequency and gentle motions such as controlling a hovering helicopter. Only motion platforms with unusually large translational movements such as the NASA VMS[6] at Ames Research Center, California, USA and the DRA AFS[7] at Bedford, UK can provide effective motion cues at frequencies down to around 1rad/s (0.16Hz).

Dynamic motion seats can provide another source of motion cues. The DRA has shown that a dynamic seat can provide the vertical motion cues that are required to perform hovering tasks[8]. This system provides cueing that pilots can interpret as a motion cue by stimulating the pilot's kinaesthetic and touch sensors without any real motion, but it is not identical to physical cues in flight and only partly simulates the wide range of sensations experienced in flight. This makes it difficult to be confident that dynamic seat cues will be interpreted consistently in a wide range of situations. Until more experience is available it would be wise to limit the use of these indirect cues to those tasks where pilot dynamic control is not critical, i.e. for training rather than clearance tasks.

Modern highly-damped command control systems would appear to be less sensitive to the absence of motion feedback to the pilot since he is not required to contribute the degree of lead compensation that is aided by motion cueing. However, absence of cockpit motion can completely mask potential biodynamic feedback problems resulting from the large acceleration/control-deflection gradients that may accompany the short response-times that are characteristic of these systems. This problem has been seen in the development of several systems that utilised force-controllers. Flight test results dictated the need for filtering of the controller output or reverting to position controllers. If a motion simulator is to accurately represent this type of problem, special attention must be given to the dynamic performance of the motion system, for the problem is likely to appear in the form of oscillation frequencies near 2 Hz. This implies that the system geometry, inertia, and dynamics must be correctly represented, and also that there is sufficient acceleration at the pilot's position to stimulate the problem. Finally, simulation lags must be kept as low as possible to avoid exacerbating the problem.

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* 'Transport delay is the total simulator system processing time required for an input signal from a pilot primary control until motion system, visual system, or instrument response. It is the overall time delay incurred from signal input until output response. It does not include the characteristic delay of the airplane simulated.'

Absence of motion cues has been indicted for failure to predict serious Pilot Induced Oscillation (PIO) problems in Fixed-based simulation. Reasons for this include the possibility that the pilot in the simulator has not been motivated to elevate his control input gain to the point of inducing dynamic instability. Popular explanations are

i in the absence of normal flight cues, the pilot adopts significantly reduced gains in order to produce satisfactory performance in tasks which are not severely time-dependent, and

ii the increased pilot gain induced by the often severe penalties of unsuccessful performance in flight is difficult to reproduce in the artificial world of the simulator.

Recent studies of this problem have resulted in the suggestion that exaggerated time dependencies and performance targets, as well as elements of surprise, be added to the simulator tasks to increase the chances of exposing PIO tendencies. This technique has been used successfully in recent studies at DRA, Bedford[7] using the Large Motion System of the AFS.

As discussed in Appendix B, acceptance tests of the NASA Space Shuttle landing control systems were conducted in motion-based simulation more than a decade ago. In that case, the customer, NASA, was not willing to accept the results of fixed-base simulation assessments as adequate support for the necessary design decisions. Cockpit motion proved valuable to the assessments, and has been sought by the program in all similar assessments since that time. At the request of the Air Force, the NASA VMS facility is also being used in early developmental acceptance tests of a large military transport aircraft that utilises a fully electronic command control system. At first sight, it appears that this new simulation is identifying undesirable lurching of the cockpit that leads to destabilizing pilot control inputs, behaviour that was not exposed in a fixed base simulator.

3.1.1.3 Harmonisation of cues

In the past, arguments have been made for matching the lag characteristics of visual and motion systems, but current evidence would support minimising the lags independently, never lengthening a delay to match the slower element. However, motion cues must occur with or before visual cues if they are to provide advanced warning about future changes in aircraft motion.

3.1.2 Situation cueing

In addition to responding to dynamic cues, pilots also require a wide range of situation information from which to plan and implement changes in flight state. In broad terms, situation information identifies the current state of the aircraft and its environment so that a pilot can decide whether or not to initiate a change. This may be an urgent need, e.g. collision avoidance, or longer term, e.g. approach of a navigation way point. Information comes from a wide range of different sources in flight and there is usually significant redundancy of information, which is often important in assisting a pilot to identify and confirm situation changes rapidly. Typical sources are the visual scene, motion, cockpit instruments, sounds, vibration, and, on aircraft with direct linkage to flying controls, control loads. Because of the redundancy of information and the need for consistency with flight situations it is important that situation cues are adequately harmonised to prevent confusion from apparently conflicting cues.

The importance of particular situation cues is tied directly to the tasks to be undertaken on the simulator. However, cockpit instruments are needed for all tasks, and visual scenes for nearly all tasks. Motion, sound, etc. should be chosen after appropriate analysis of the tasks.

Although they will always be available as important sources of information, cockpit instruments should not be used as an alternative to visual, motion or other cues if this significantly delays recognition of important situation changes and thus impairs response performance. An obvious example would be to use instruments to identify an engine failure during take off. The pilot will eventually notice that his airspeed is not increasing normally and that there are other indications, perhaps including an engine warning, but the situation will need to be verified before taking appropriate corrective action. If motion and visual scene are present then powerful yawing motion cues will alert him to the problem immediately in an unambiguous way that is very similar to that on an aircraft. It is also important that cockpit instrument displays are configured as they appear in the aircraft and have the same dynamic response, e.g. height rate instruments should include representative pneumatic lags and any accelerometer signal should be calculated at the correct location of the accelerometer relative to the aircraft centre of gravity.

Requirements for all aspects of visual cueing systems, such as field of view (FOV), resolution, contrast, brightness, and scene details, including cultural features, texture and contouring, are closely dependent on the tasks. In most cases pilots will be the final arbiters on the adequacy of a visual system for chosen tasks, although in all cases the task must be clearly identified to the pilot and the possibilities of changing tasks to accomplish the required certification objective should be considered before rejecting a particular simulator configuration. The use of artificial visual features can be acceptable as long as it is clear that they stimulate the same control response and strategy from pilots as would occur in flight.

Simulation of the flight tasks of typical transport-category aircraft can be adequate with a limited and fixed forward FOV. A typical 50° × 35° window will support the tasks of take-off and final approach. An additional window providing more lateral view is helpful in approach pattern turns, but seldom can be considered necessary. The simplicity of this requirement is due to the fact that the predicted flight path of interest is almost always constrained to the limited forward field of view. The required FOV grows larger for simulations of the landing flare and touchdown, of tactical manoeuvres involving high turn rates near the ground, and in air-to-air combat. In the simulation of hovering manoeuvres with helicopters or VTOL aircraft, FOV requirements are also greater because of the essentially omnidirectional capabilities of these aircraft. The instantaneous flight path is often displaced as much as 90° laterally or vertically from the aircraft's reference axis.

The desired level of scene detail is an inverse function of the distance between the viewer and the terrain objects. Some minimum value of "spatial density" (contrasts per unit viewing area) is necessary to effectively define a ground plane or other surface. Thus, simulations of hovering landings or "nap of the earth (NOE)" flight most challenge the technology, and benefit greatly from the more recently developed capability to represent surface textures in photographic detail at close range. Precision hover in the presence of even a well-detailed simulated ground plane still appears more difficult in simulation without extensive motion than it is in flight, but with the provision of a reasonable field of view and pseudo motion from a dynamic seat, simulation can be adequate for many hovering tasks. Important to the effectiveness of the visual simulation is the provision of familiar near-field details that provide a sense of scale, and thus a sense of proximity. Accurate perception of self-motion is dependent on an accurate perception of distance from the visual cues. In the real world, as a surface or objects are approached, higher and higher levels of detail are perceived, and at close ranges, normal binocular depth perception can become a factor in assessing proximity. In the visual simulation, neither of these factors is normally present. Related to the level of detail is the resolution provided by the visual display devices. Modern systems are producing of the order of one million pixels per "window". If each window is not expanded to diagonal sizes beyond about 70°, the resolution is adequate for most flight tasks other than those requiring identification of distant targets, where about 4 times better resolution is needed.

Some compensation for deficiencies in downward FOV and surface detail when hovering has been obtained by altering the scene to include numerous objects closer to hovering eye-height. A unique approach has been taken in a VTOL controls system development program being conducted at NASA Ames Research Center. For hover tests with the YAV-8B aeroplane, several arrangements of target boards are suspended at altitudes between 50 and 100 feet above the ground. These "real" visual scenes are easily simulated in a laterally disposed three-window scene, and the results of flight and simulator tests[9] have confirmed sufficient equivalence of the visual cueing situations for the selected tasks.

Another important situation cue in military flying is the normal acceleration, or 'g' force. This cannot be directly provided on simulators, apart from a few specialist centrifuges which are very limited in other simulation capabilities. Pilots are usually presented with some of the secondary cues associated with 'g' forces, such as inflation of g-suit, dimming and tunnelling of visual scene, buffet, and indications on a 'g' meter. Meter indications are probably the least useful in most circumstances as pilot attention is often on the outside visual scene during high 'g' manoeuvres and reading a meter is very distracting. Voice readings of 'g' levels may help if there is no other speech activity.

In the real world of flying, the pilot records and catalogues, more or less automatically, a wealth of other situation cues. Good examples are the vibrations induced in aircraft by buffet in either transonic manoeuvring or when approaching the stall, etc. Also, the feedback to the stick of forces on the aircraft control surfaces are at times automatically used to anticipate some peculiar aircraft behaviour. A special case is the difficulty encountered in keeping control of the aircraft in the dynamic environment often found at the boundaries of the flight envelope, e.g. the all axis accelerations of a departure or spin are critical, and their careful examination, in the correct combination, is of paramount importance to assess or ensure the ability of pilots to cope with the situation.

The unique aerodynamic noise of a spinning aircraft at high yaw rates, and its distribution or direction in the cockpit, combined with the side-force acceleration, can be of the greatest value in helping the pilot to recognise the situation, but not necessarily contributing to its solution; e.g. the lateral acceleration in spinning often prevents the pilot from getting a centred position of the stick which is sometimes essential for recovery. In this case, the pilot is faced with a conflicting situation: relevant noises and lateral accelerations are a clear indication of spinning (sometimes, were it not for these cues, it would be difficult to distinguish the spin from a tight spiral) and assist spin recovery procedures. The recovery is made more difficult by the accelerations themselves, the effect of which is to confuse the pilot about the position of the controls (particularly stick position).

Engine surging or stalling is another good example: some types of "soft" stall are only sensed by vibrations induced in the aircraft structure, or by buffet induced noise, or by the special smell immediately present in the cockpit through the air-conditioning system. At the same time, engine stall can be mistaken for pneumatic valves snapping loudly closed or open. Much in the same way, the rumbling of an air-conditioning pipe can be mistaken for an engine surge, or for intake buzz. It is therefore a special combination of cues that allows the pilot to recognise a situation, before relevant instrumentation is examined or even in the absence of suitable instrumentation.

It is also essential to investigate whether it is necessary to reproduce in the simulation realistic cues with a high degree of fidelity, or whether the pilot can assess the system accurately, knowing that secondary cues are absent or reduced.

3.1.3 *Pilot adaptability and subjective assessments*

In addition to perceiving cues humans also learn to process and interpret this information so that they can choose actions that are most likely to achieve their requirements. Pilot training and practical experience over many years teaches a range of 'standard' responses to cues and any mismatch, or absence, of these cues in a simulator will require some adaptation of these learned responses. If the differences between flight and a simulator are sufficiently small then pilots will easily adapt to the system and achieve similar task performance. Subjectively they may find little difference in handling qualities and workload, but there will always be some difference in control activity if the simulation differences are significant for the task. Larger differences can lead to significant changes in control strategy when compared with flight and pilots will usually find the simulation unsatisfactory even though performance may be similar to that in flight. The degree of adaptation also influences the time required for pilots to familiarise themselves with the simulation.

Relevant measures of the amount of adaptation can only be determined where the subject pilots have established their competence with the class of aircraft and tasks to be simulated. Pilots without a high level of relevant competence will not be able to judge the validity of a simulation. Although they will usually be quick to learn how to manage the simulation, they will have no way of knowing whether their control responses and strategies are representative of flight. In this regard, relevant competence may be provided by test pilot skills in evaluation as much as operational experience.

The following comments stem from opportunities to conduct or to witness many simulator assessments of novel aircraft configurations, or new control or guidance concepts. Overwhelming factors in the effectiveness of these evaluations have been the background each evaluation pilot has brought to the simulator in terms of flight and flight simulation experience, his experience in the particular simulation facility, and the opportunity he has been given to become fully educated and trained regarding the system he is evaluating. The effective simulator pilot appreciates that in the presence of cue degradation in simulation, aircraft response characteristics will be harder to identify than in flight, thus the familiarisation process will take longer. He will insist on being given the time to achieve a performance plateaux. He will not accept performance levels significantly lower than he would accept in flight. Because he has operational or test experience in related flight and simulator piloting, he will have a reasonable basis for extrapolating his simulator assessments to a flight environment. He should be able to qualify his confidence in the evaluations with his own assessment of the fidelity of the simulation. He believes that simulation, properly utilised, is a valuable tool in the development and acceptance of aircraft and aircraft systems. The test conductor is seriously constrained if a pilot with this experience and motivation is not among his evaluators.

There is every reason to expect that when the pilot is first introduced to the simulation of a familiar aircraft, though it is accurate in every sense except for reduced motion feedback, simplified visual cues, and probably increased latency, he will have some difficulty subjectively accepting it as the equivalent of flight. In all probability, pilot workload will be higher, and performance reduced. It is also probable that the pilot will not perceive reduced levels or absence of motion feedback as the source of his difficulties, since these cues are normally perceived at the sub-conscious level. His continued exercise of the simulation will result in improved performance and an increased sense of simulation fidelity as he adapts to the simulation motion cues and, again sub-consciously, develops compensatory precognitive control techniques. It has been noted that in most cases where the pilot's first flight in the aircraft follows many hours in its ground-based simulation, the simulation is perceived as having been an accurate predictor of the characteristics of the aircraft, though the difficulty of critical tasks may tend to be less in the real flight environment. This dependence of subjectively sensed simulator fidelity on the order of the flight and simulator experiences is understandable. In the flight-to-simulator transfer, cues important to the pilot's mode of control have been degraded or eliminated, resulting in some level of initial confusion and performance degradation relative to flight. The reverse transfer simply adds additional cues in tasks in which the pilot quite likely has developed a comfortable level of performance in the simulator.

Workload, or stress is another factor limiting human performance and it is important that simulation has a similar balance of different contributors to the overall workload. There are often comments on the inability of simulation to create the ultimate levels of fear and apprehension that may be experienced in life threatening situations because the ultimate sanction of death is not present. This is not relevant to flight clearance activities as they deal with situations and means of ensuring safety, where the main incentive for pilots is to avoid stigma from displaying poor airmanship. However, it is important to represent the total workload experienced by the aircrew for any simulated task as the ability of the crew to respond in critical situations will often be constrained by the presence of other necessary tasks. It is strongly recommended that workload should be compared between flight and simulation when validating a simulator.

In his assessment of a simulated aircraft's basic control system and handling qualities, the pilot will normally extrapolate his experience to flight and the operational distractions he expects to encounter. If the peripheral tasks are unique and unfamiliar, they should also be included in the simulation. If the real environment requires frequent distracting interactions between crew members and/or outside elements such as traffic control or tactical command, consideration should be given to their simulation. In the evaluation of systems in tasks peripheral to the primary flight control objectives, the simulation should include stressful versions of the basic flight task. This is particularly important in those cases involving the scanning of information sources away from the basic flight displays and manual input to the systems. Consideration should be given to the importance of cockpit motion and vibration environments in the evaluation of such systems.

In the end, only the dedicated pilot can give the best evaluation of how many of the validation goals have been achieved through simulation. To offer consistency in the contribution given, it is therefore necessary that the pilot employed in the simulation be familiar with both the real system and the simulator, so that the degree of his conscious compensation is adequate to obtain both the desired validation results, and weighted judgements on its validity.

There is no doubt that flight simulation is a valid tool for acceptance testing: it may be the only way to gain experience in some phases of a programme. Once validated with flight test findings, the simulation can be a valuable tool in the clearance process and, in some instances, can be the only tool used to get acceptance of a system. The contribution of the pilot with dedicated training is, especially in this last case, as important as it is in flight testing. In this respect, good progress can be made only if the engineer-pilot relationship is tightly linked, as is usual in flight testing.

The use of research and engineering simulation has recently given outstanding results in the fields of in-house certification, customer acceptance of modification, and new issues of software. In this respect, the use of simulation has been extremely productive in the fields of flight control, avionics, and display optimisation. Also, it has been instrumental in getting customer acceptance of the intended path to be followed to implement changes or solve problems in all three areas, and so to obtain progress payments.

3.2 The Vehicle Model

For many years the creation of mathematical models of aircraft has been an important part of the process of development and certification/acceptance. Models (of various degrees of complexity) have been used to predict flight characteristics ahead of the flight test programme, and to investigate anomalies discovered in flight. They have also been used to predict performance in situations where flight testing would have been impractical, too hazardous, too time consuming, or too expensive (e.g. complex failure modes, including mechanical failures, rare and extreme meteorological and environmental conditions, or acquiring the large amounts of data required for the statistical analysis of, for example, autoland performance). Many of these models have been developed using the fullest possible descriptions of the vehicle and its control systems to ensure the highest possible fidelity. Such models often cannot be computed in real time despite restricting them to limited flight regimes or aircraft configurations. However this is not a problem when a human pilot is not an active participant in the system.

The fundamental aerodynamic and physical equations used in these sophisticated non-real-time models are an essential guide to the forms of model structure that should be developed for real-time simulation.

In piloted flight simulation, where the pilot is a necessary participant, models must run in real time with typical computational times of between 1 and 10 milliseconds within total cycle times of 2 to 25 milliseconds. This requires particular attention to the computational efficiency of models and, sometimes, simplified representation of systems, e.g. simplifying high frequency behaviour that is well outside the control response of a pilot, say above 5Hz. It will also be necessary to represent sufficient of the flight regimes and configurations for a pilot to perform meaningful tasks with significant deviations from nominal flight patterns. Such deviations may well need to go into potentially dangerous flight situations.

Where the flight mechanics are well understood, and where there is substantial background experience in aircraft mathematical modelling, the development of models for piloted simulation should be relatively straightforward. This may not be the case for unusual flight conditions (e.g. very high angles of attack), novel aircraft configurations (e.g. ASTOVL) or any vehicle or flight condition where the flight mechanics are complex or not fully understood (e.g. helicopters). In many cases, the simulation models may be developed simply and directly from (or alongside) models used for non real-time applications. But even if circumstances dictate that simulation models are developed "from scratch", verification of the responses of the simulation model can be achieved in part by comparison with available non real-time models. Furthermore, as additional wind tunnel, engine test and flight test data become available, similar validation checks and refinements can be made to both non-real-time and real-time models.

The specific requirements of model verification should be given due weight when defining the envelope and configurations which are to be tested either in flight or in the wind tunnel. During the early stages of the development programme, data for model development or verification will be sparse, but there may still be a requirement for an "adequate" model for piloted simulation tests. In this situation, theoretical predictions, engineering judgement, and experience from previous aircraft will need to play a part. But the limitations of the "immature" models which can be developed at this stage of the project must be recognised and accepted. Such models must be used with caution, for "broad-brush" or exploratory studies only. They should be checked and refined as soon as opportunities arise, and effort invested in defining and implementing such models in a modular way, to facilitate future refinements, will be very well rewarded.

As to the scope of the model which needs to be developed (and hence by implication the scope of the verification process), the key consideration must be the objectives of the simulation trials programme. Thus the aspects of the aircraft which are to be demonstrated for certification/acceptance by simulation must be defined and documented in advance in order to avoid nugatory effort being expended in unwarranted sophistication of the model and its verification. Thus, for example, if touch down and ground-run dynamics are to be certified by simulation, quite elaborate modelling (and verification) of the gear and tyre characteristics would be appropriate. On the other hand, if these aspects were to be certified by flight tests alone, a much more rudimentary undercarriage model would suffice, and verification of this aspect of the model would be a much less demanding business.

3.3 Systems Modelling and/or Hardware Integration

The simulator is obliged to use a mathematical model to represent the aerodynamics, engine, undercarriage and sensors of the subject aircraft. However, in the case of avionics and equipment, there is a choice between interfacing the simulator to actual flight hardware (stimulation), creating software to model the system (simulation), or using aircraft software in the general purpose computers of the simulator (emulation). Each approach has its advantages and disadvantages in terms both of implementation and validation.

Using actual flight standard hardware has the advantage that the true equipment characteristics are provided in the simulation and experience in the simulator may contribute directly to refining and developing the system in preparation for (or in support of) flight trials. The simulator can readily keep abreast of, and check-out, any equipment modifications, since hardware and software changes can be implemented immediately, and the simulator will capitalise directly on the configuration control philosophy which is bound to be applied to the flight-rated equipment. Further, the use of flight hardware may be the only practical option if the details of the model represented by the embedded software are classified and cannot readily be released for simulation or emulation in a general purpose computer. On the debit side, the difficulties in interfacing hardware to the simulator may be significant, particularly if the system is digital and needs to run asynchronously with the simulation frame rate. Additional software effort may also be needed to model sensors and communication protocols to the level of accuracy expected by the flight hardware. The capital cost of flight-rated hardware may be a disadvantage and, if the equipment is newly-developed, availability of units for simulation may be problematic. Significant delays may occur if the need for "fixes" or refinements arise during testing, since these tasks will generally be the responsibility of a subcontractor supplying the system. When assessing the benefits of using flight hardware to help 'qualify' airborne equipment it must be remembered that, because of the different environment of the simulator as compared with flight (e.g. g-forces, vibration, temperature), the simulator can only address the functional certification of the equipment and not its operation in the environmental conditions representative of flight. Finally, the flight hardware may be unsuitable for use in the simulator because it has no facilities either to suspend operation while the simulator is in "freeze", or to enter known failure states on command as would be needed to simulate a flight in various failed conditions. These last points are now being addressed by equipment manufacturers, who can provide such facilities (incorporated in such a way that they cannot be evoked when installed in an actual aircraft) in accordance with the ARINC standard 610. However, to date such facilities (developed for application in training simulators) have only been implemented for civil aircraft.

One advantage of 'simulating' the system (i.e. writing software specifically to represent the airborne equipment within the simulation computers) is that the simulator development team have direct control over the development of the representations. The level of detail embodied, and the sophistication of the modelling of failure states, can be managed to suit the needs of the simulator trials programme. On the debit side, the effort required to develop an adequate representation of complex airborne equipment may be totally prohibitive (perhaps 10's or even 100's of man-years for a full flight management system). Furthermore, data which adequately defines the performance and detailed responses of the system may be sparse and inadequate.

This is particularly likely to be true of failure modes. These factors will not only hinder development of the simulation software, but also possibly preclude adequate verification of the end product.

The third option, that of 'emulating' the system by using the aircraft software in the general purpose computers of the simulator, has been made possible by the increasing use of high level languages in airborne systems as a consequence of the US DoD mandating the use of the ADA programming language for all flight software. This approach has major advantages, especially when considering the ever increasing size and complexity of modern airborne software, whilst avoiding many of the disadvantages of the other two approaches. Complex software systems can be installed and verified in a matter of hours, and additional features to cover failure modes or simulation specific functions can be readily introduced. Further, interfacing the aircraft software with the simulation software is often easier than interfacing the equivalent hardware. On the debit side, the difficulties in modelling the flight computer hardware and interfaces may be significant, in particular timing issues associated with its internal and external communications. This is particularly true if the hardware has multiple CPUs with software communicating between CPUs during any frame-time.

Thus the choice between flight hardware, simulator software or aircraft software is unlikely to be straightforward. The more complex the software and/or the hardware, the more compelling becomes the argument for using the actual flight software and/or hardware in the simulator. The difficulties of simulating sensors to provide appropriate signal inputs, and of simulating flight hardware characteristics to provide the appropriate host environment for flight software, e.g. bus traffic, timing, etc., should not be underestimated. Each case must be considered on its merits, but the requirements and objectives of the simulation must remain paramount and be clearly defined. Where modelling uncertainties remain, and are of concern to the certification authorities, a measure of the significance of the uncertainty may be obtained by varying the critical parameters.

Because they can be examined in safety, very comprehensive evaluations of system failure modes and transients can be conducted in simulation of the most critical flight conditions. Tasks can be imposed upon the pilot in any rational combination of primary tasks together with appropriate secondary tasks. It has been generally observed that in the fixed base cockpit, recognition and control of failure transients are inhibited, resulting in overly pessimistic assessments of the control problem induced by failures. It is strongly recommended that simulator assessments involving failure transients include cockpit motion capable of providing at least an alerting function.

3.4 Scenario and Environmental Modelling

Simulation offers opportunities to test aircraft and systems concepts in environments and scenarios that are impractical or impossible to establish in flight tests. Since these "worst case" conditions may define the acceptability of the subject system, the fidelity of their simulation is of prime concern. Winds, turbulence and visibility are factors directly challenging the pilot and the vehicle. These and other operationally induced distractions and stress can add to the validity of the simulator assessments, especially those of peripheral systems associated with navigation, communications or weapons. However, because attenuation of cueing in simulation can exaggerate the basic flight control workload, care must be taken to avoid scenarios that for the same reason further elevate tasks to improbable and unrealistic levels of difficulty.

3.4.1 *Turbulence and Winds*

Long-accepted methods of modelling turbulence and its effects on aircraft response appear to be adequate for most evaluation activities involving fixed-wing aircraft. It should be noted, however, that the control tasks presented to the pilot by simulated turbulence tend to be exaggerated, particularly in the total absence of cockpit motion. With conventional motion systems, the high frequency portions of the turbulence can be sensed, but flight-path disturbances due to the lower frequency components are still not perceived in the normal sense. This could explain the low opinion pilots hold regarding the ride quality provided by simulated turbulence. Conventionally modelled turbulence presented in the context of the large motion envelope of the NASA VMS has been accepted as realistic.

Representations of winds, and discrete low-frequency wind variations more commonly referred to as shears, are most important for the simulation of landing and take-off manoeuvres. To present the critical cross-wind landing task with fidelity requires effective modelling of the winds and turbulence, as well as the aircraft's landing gear. It is helpful to include the normal wind velocity gradient with altitude. In general, "cross-control" manoeuvres present exaggerated difficulty in the absence of motion cueing, so it is especially important that the evaluation pilot be given the opportunity to familiarise himself with the task.

3.4.2 *Tactical Scenarios*

The newer visual simulation capabilities coupled with large capacity computer facilities provide the means to create very elaborate tactical combat scenarios involving several aircraft. In these situations, the piloting task can become a contest; an engrossing competitive game. Unfortunately, particularly if the scenario does not relate strongly to his past experience, the evaluation pilot may sometimes fail to give appropriate consideration to the level of fidelity of the task presented.

3.5 Software Considerations

The validation process is essentially an assessment of the adequacy of the total simulation for the intended certification tasks. Thus it strictly addresses the observable performance of the hardware and software which together provide the complete simulation. Poorly designed or engineered hardware may possibly achieve adequate performance on occasions, but it may be "temperamental", yielding results which cannot be repeated with confidence, or even failing totally. Validation of such equipment (if possible) is slow, frustrating and very costly. Fortunately, the importance of good design and engineering of hardware is generally well understood and such difficulties are unlikely to arise. Sadly, the importance of good software design and software development practices is less widely appreciated. But the scope for shortcomings in these aspects to cause obscure malfunctions which can frustrate or undermine validation is far greater than for hardware. Thus effort invested in software design and in good software development practices will be repaid in the course of validation. Good software design will enforce a modular structure. Modules can be tested individually and then together. Static and dynamic testing identify errors and build confidence in the correct operation of the software. Testing of software cannot prove correct operation, only the absence of errors within the scope of the tests. Even so, it is a vital foundation for the eventual validation of the complete simulation.

Strict configuration control of software at all levels, including programs, data and system software, will be vital if results of early tests are to retain their validity. Fortunately, software packages to enforce configuration control on the software development process are now available, and will become increasingly essential as the volume of software associated with simulations continues to rise.

Some of the software required for the simulation may correspond directly with software already created as part of the aircraft development programme: for example, aerodynamic or engine models for simulation and for non real-time development studies, or software to simulate on-board avionics and the software within the actual avionic equipment. In some cases, perhaps increasingly so with the emphasis on high level specification and design languages and portable software, it may be possible to re-use (or modify) the existing software. Any software so used must have been previously validated and be fully supported by design and test documentation. In other cases, the requirements of real-time operation, or the unavailability of compilers for a particular language on the real-time system, may mean that the software for the simulator has to be developed from scratch. These two approaches to providing software for the simulator are quite different in their implications for software verification. Re-use of "common" software substantially reduces the burden of verification. However, it is unlikely that the software can be re-used without at least minor modifications, and thus a requirement for verification will still remain. In contrast, if the simulation software has been developed independently, in a different language and using different compilers, a very substantial verification effort will be needed. Nevertheless, there is one significant advantage in this approach because the redundancy afforded by the independent development of the simulation can provide a powerful tool to expose any errors in either implementation of the software.

Choice of language for simulation software may similarly be influenced by such factors as real-time efficiency, compatibility with pre-existing software, company expertise, and availability of proven (verified) compilers. Eventually Ada is likely to become the obvious (perhaps the only) choice, but at present many of the above factors may point to the adoption of a less sophisticated, but more generally used languages such as FORTRAN. However, the likely lifespan of the simulation model should also be considered. The most intensive use of simulation is likely to arise during the preparation for, and achievement of, certification/service acceptance. Nevertheless, a capable and validated simulation is a substantial investment and provides a facility which should be of ongoing usefulness throughout the complete life of the project. Furthermore, in the case of military aircraft, the procurement agency may perhaps in future require that the simulation software be made available for application to training simulators. Equally, in the case of civil aircraft, the manufacturer may be able to sell the software to a training simulator manufacturer, or possibly establish some co-operative agreement. The prospect of such schemes would further enhance the attractiveness of Ada.

A more detailed check list for software configuration management is presented in Annex C.

4 VALIDATION TECHNIQUES

The validation process is closely related to the basic assumptions made when designing a simulator. A similar logical process can be adopted for validating any simulator but the role of that particular simulator must be taken into account at each stage. In many cases it is possible that the simulator is not intended to be representative of all the aircraft's phases of flight. However, it is often desirable to allow the simulator to enter these phases so that a pilot can transition between other phases of flight in a continuous manner. In such instances the validation process should reflect this by appropriate restrictions on the validated envelope, which would not prohibit the use of other parts of the envelope for transitioning between validated areas.

From a validation point of view a simulator has two main components: the mathematical model and the cues presented to the pilot to allow interaction with this model. Usually the process is one of quantitative and independent validation of the model and cues followed by closed loop quantitative assessments and subjective evaluation using a pilot-in-the-loop. The stages in the process are illustrated in Fig 2.

4.1 The Validation Process

Validation of a simulator is a process of demonstrating by objective and subjective testing that the theoretical model and the physical simulator together form an adequate representation of the real system for the intended application or task. Simulator generated output data are compared to real system data obtained by ground or flight tests (Fig 3). Thus, validation requires real world data for comparison with simulation results.

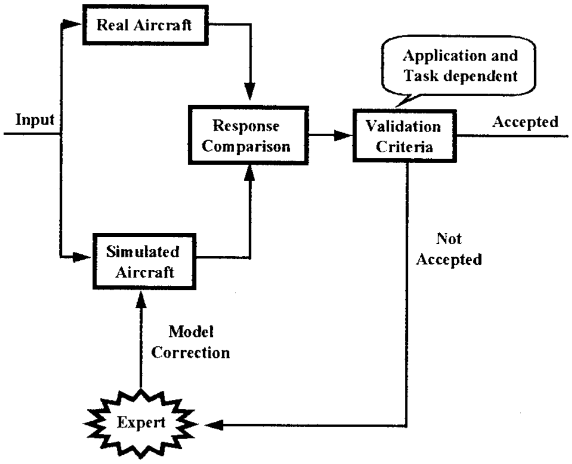
Real Aircraft
Application and Task dependent
Input
Response Comparison
Validation Criteria
Accepted
Not Accepted
Simulated Aircraft
Model Correction
Expert

Fig 3: Validation of a simulation module

In order to obtain adequate real world data which are suitable for simulator or model validation some form of hardware testing must be conducted e.g. bench tests, subsystem tests and flight tests. This can be a problem area and it is described in section 4.4 in more detail. Additionally, the validation process requires the definition of the required simulation accuracy (criteria of acceptability) to decide whether or not the validation is complete. Any "validation criterion" naturally depends on the specific application. For piloted simulators, all elements of the models of the aircraft and its systems must behave so that the differences compared to the real world remain within the resolution capabilities of the pilot. At the same time the cues that permit the pilot to perceive the behaviour of the aircraft must be adequate for the task to be simulated. To the pilot, this means that the simulator responds like the aircraft, that the same performance goals can be achieved with the same workload as in the aircraft, and that he uses the same control strategy and responses as in the aircraft. On the other hand, if simulation is used for hardware validation (hardware-in-the-loop-simulation) the model output must be identical to real world data to a higher degree than for piloted operation. For example, for digital systems the data timing must be identical, otherwise the simulation results could be totally wrong. In addition to the application of objective test procedures for validation, which will be described in section 4.7 in more detail, subjective testing procedures (pilot assessment) remain absolutely essential because models which are able to describe pilots perception tolerances, especially for stick force, motion and visual cues, are not available.

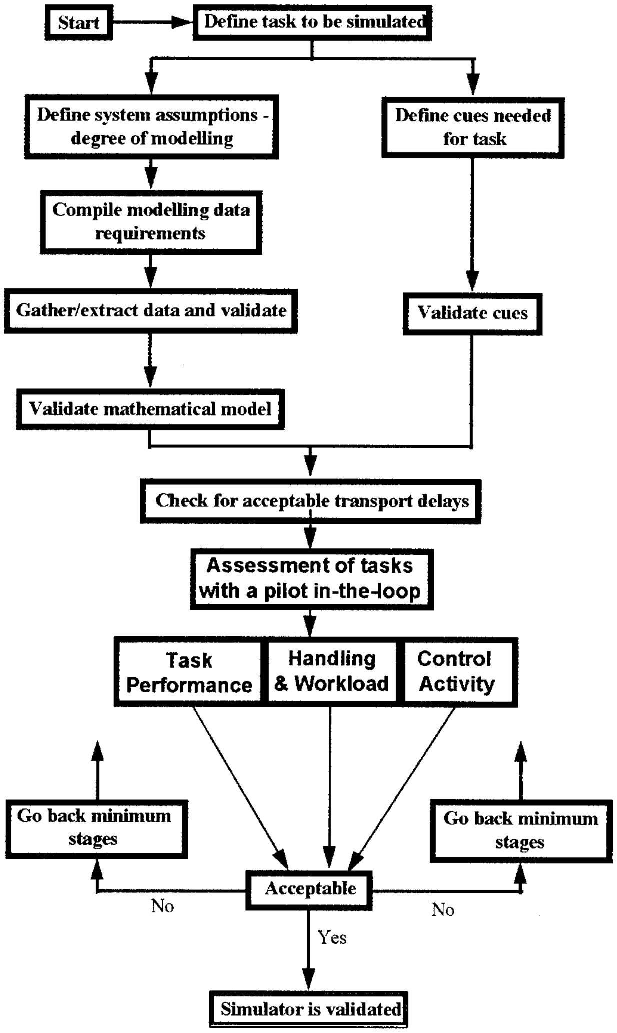
Start
Define task to be simulated
Define system assumptions - degree of modelling
Define cues needed for task
Compile modelling data requirements
Gather/extract data and validate
Validate cues
Validate mathematical model
Check for acceptable transport delays
Assessment of tasks with a pilot in-the-loop
Task Performance
Handling & Workload
Control Activity
Go back minimum stages
Go back minimum stages
Acceptable
No
No
Yes
Simulator is validated

Fig 2: Stages in the validation process

Usually, validation of a simulator system is done from "the bottom up". This means that the subsystems will be validated or verified separately. After these sub-validation tests the total system including all functional interdependencies will be validated in final acceptance testing.

4.2 Task Definition

The overall capability of a simulator is a combination of the individual tasks which it can represent. Tasks often overlap to a great extent and are fundamental to both the simulator design and validation processes. The starting point is a clear understanding of the task. Considerations to be taken into account for the landing approach task will be quite different from those for air-to-air refuelling, for example. The task may be very specific, as in these two examples, or be of a more general nature covering large parts of the aircraft's flight envelope, e.g. air combat.

Having defined the task, the flow of activities can diverge into two separate but not completely independent paths. The first of these considers mathematical modelling and the second, the cues required.

4.3 Modelling

The data package needed for simulation depends to a large extent on the degree of modelling required. At the heart of every flight simulator is some form of aircraft model; this can vary from a simple linearisation to a complex non-linear model. Other considerations which arise are associated with the modelling of aircraft hardware. Two examples are given below: the aircraft powerplant, and control surface actuation.

In order to simulate an engine for the purposes of hardware development, it is often necessary to represent its many inner loops, non-linearities and high frequency characteristics. For a pilot-in-the-loop engine model, considerable simplifications can often be applied without the model becoming significantly different within the pilot's control bandwidth. Often, an equivalent model can be derived which gives end-to-end static and dynamic characteristics up to the highest frequency relevant to a pilot (c. 2-4Hz), which are very similar to a much more detailed model.

A similar argument applies to actuator modelling. Again, there are high frequency modes of operation within the actuator control loops which may well simplify to a second order or even first order transfer function representing demanded surface position to actual position. However, such a simplification may not be possible in all cases, particularly if the performance of the hydraulic actuator, e.g. acceleration & rate limits, is affected by control loading.

Once the degree of modelling of the component models of the simulation has been established, a dataset requirement can be compiled.

4.4 Modelling Requirements

For mathematical modelling, data is required both to carry out the modelling and then to validate it. Further, some of the validation data must be independent of the modelling data to ensure that any errors introduced during the modelling process are not confirmed during the validation process: eg validation could take place at different/intermediate flight conditions as well as the flight conditions used for defining and deriving the model(s). The data requirements for modelling and validation may also be different: for example, modelling may require intermediate measurements if, for example, stick dynamics, actuators, sensors and flight control models are to be distinguished from the aerodynamic model, whereas validation data usually addresses the end-to-end responses of the total vehicle. Typically, validation data would take the form of time histories and frequency response plots.

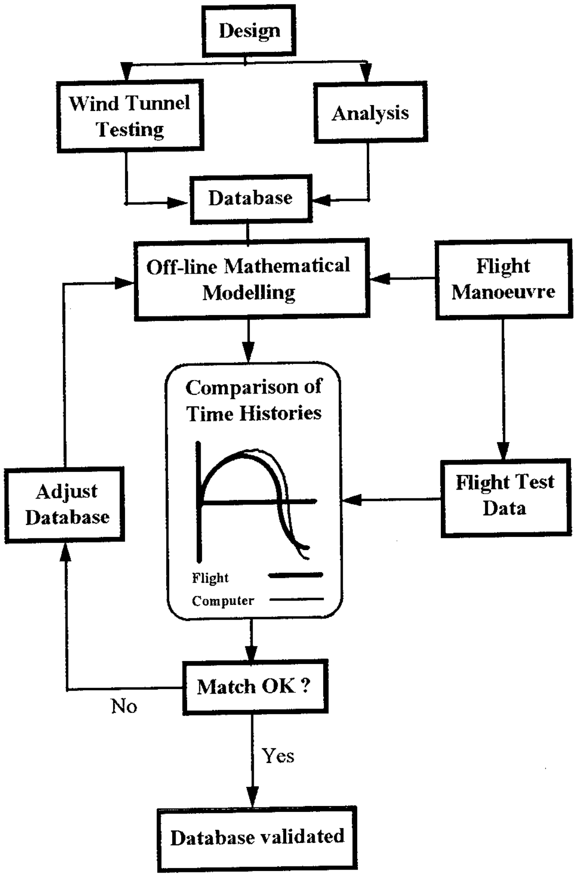

Fig 4: Mathematical Model Database Validation

The data itself is often acquired from multiple sources, such as wind-tunnel results, analysis and flight test data. Existing computer models of the aircraft or systems which may be real or non-real time are often used for development. The data used for these models can be a good source for the flight simulator. Also, the response or outputs from these models can provide validation data for the simulator provided they themselves are first validated. Fig 4 shows the method by which this happens.

But nevertheless, simulator validation requires real world data (flight test data) to compare the simulated behaviour with the real flight vehicle. This real world data package should be used as a reference for response comparison. Therefore, it is very important to establish how good these reference data are and how they are collected. From a simulator validation stand-point it is necessary to define the required data very well and to make specific flight tests to get the right data which are adequate for the validation process. Up to now the

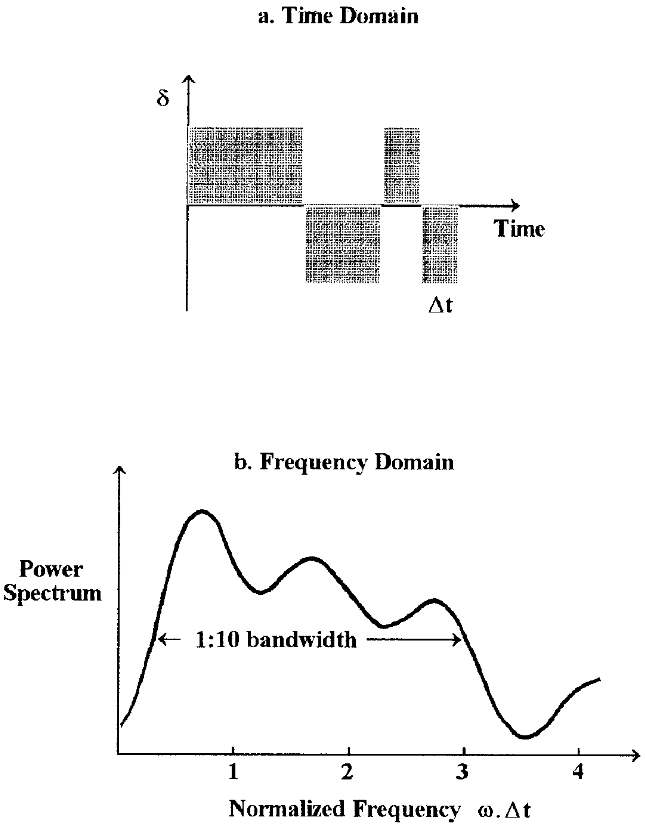

Fig 5: Wide bandwidth input signal for aircraft or system excitation

simulator contractor has had to live with flight test data which have been measured during the prototype and certification flights. But these data are often not suitable for the validation process. For instance, it could be possible that the full bandwidth behaviour of the aircraft is not excited during certification flight testing because it is not required for this purpose.

Therefore, it is very important to define the input/output signals to get data which can be used for simulation validation. Flight test procedures are needed to produce data which can be used for the special simulator validation process.

Flight test data must be corrected so that the measurement errors are eliminated. This can be done by compatibility check procedures and data reconstruction methods [5].

Suitable flight tests are:

- computer generated input signals which excite all the aircraft dynamic modes (e.g. 3-2-1-1-signals, Fig 5).
- frequency sweeps in each control axis to extract control system frequency response.
- special manual or computer generated manoeuvres.

Another common component of the modern aircraft simulator which is becoming increasingly significant is the flight control system. As we move towards aircraft with higher degrees of relaxed stability, we find the flight control system not merely augmenting aircraft handling but having a gross effect of stabilising a naturally unstable vehicle. Very often, the definition of a flight control system, whether analogue or digital, can be obtained precisely. Implementation of the control system into a mathematical model is usually a relatively straightforward process compared with the aerodynamic model, where data may be available with less than 100% confidence.

Models may be derived from flight test data by applying parameter estimation or identification methods[10,11,12,13]. These methods, which can be applied either in the time or frequency domain, give a nearly perfect matching of the time response and deliver the best estimation of the relevant model parameters (see Figs 6, 7). An advantage in using these methods is the elimination of the need for visual judgement of comparisons between actual and model time histories. The methods include estimation of instrumentation errors, a weighted overall measure of mismatch and information on the confidence levels associated with individual parameters, i.e. a measure of how appropriate the test and the model were for defining any particular parameter. Further, these methods can be used for non-linear systems, systems with noise, and systems with time delays. However, considerable care and skill is needed in formulating an appropriate model.

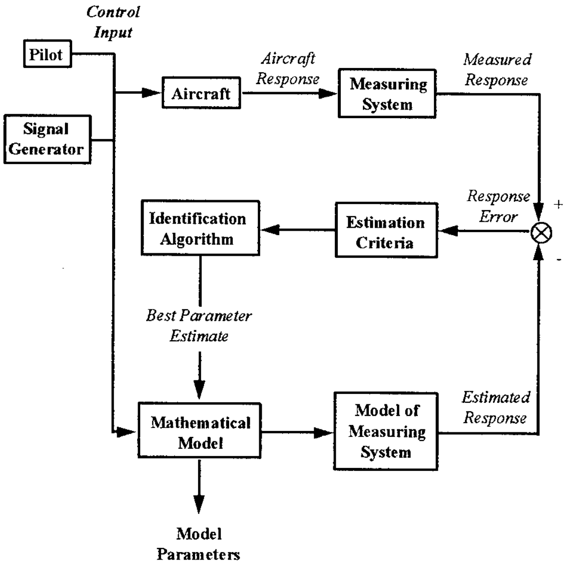

Fig 6: Principles of the Parameter Identification Process

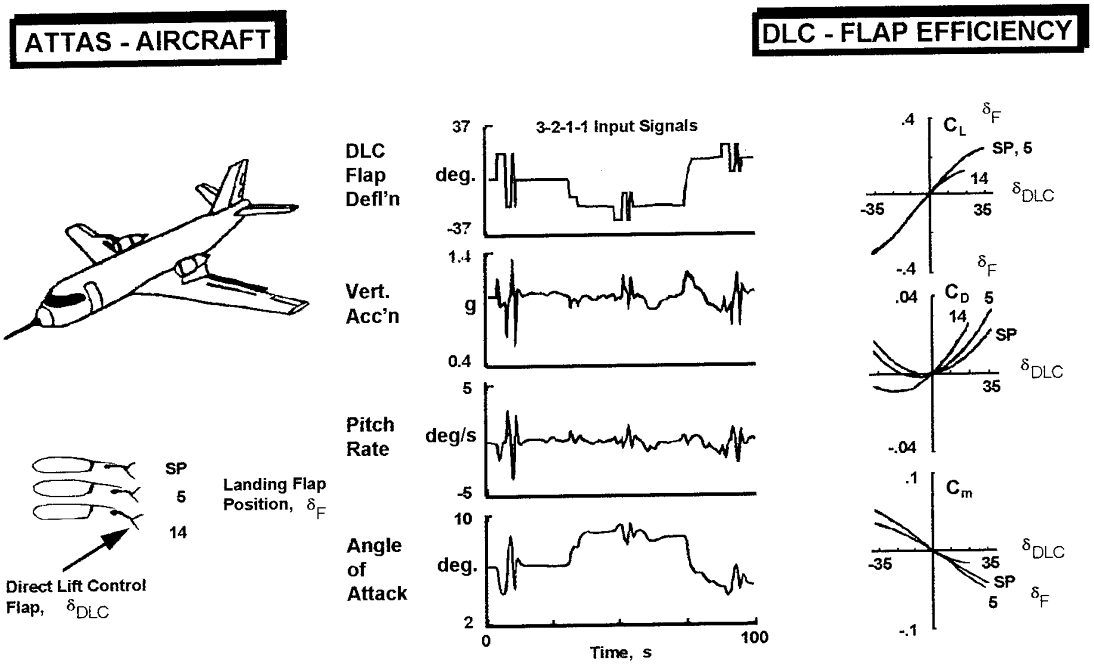

Fig 7: Aircraft Parameter Identification

Additionally, the identification procedure can be used for subsystem identification such as actuators (see Fig 8), and sensors[14]. For instance, sensor bias or incompatibility with other sensor signals will also be identified in the process. The only requirement for using these techniques is to apply suitable system excitation inputs such as the 3-2-1-1 signal, which can be generated very easily by the pilot or, better still, by the on-board computer system.

It is strongly recommended that, during the prototype testing phase of an aircraft, flight testing should be expanded to provide the model parameter data package as a reference for simulation modelling and validation. This would be a break-through in simplifying the simulator modelling and validation process. At the same

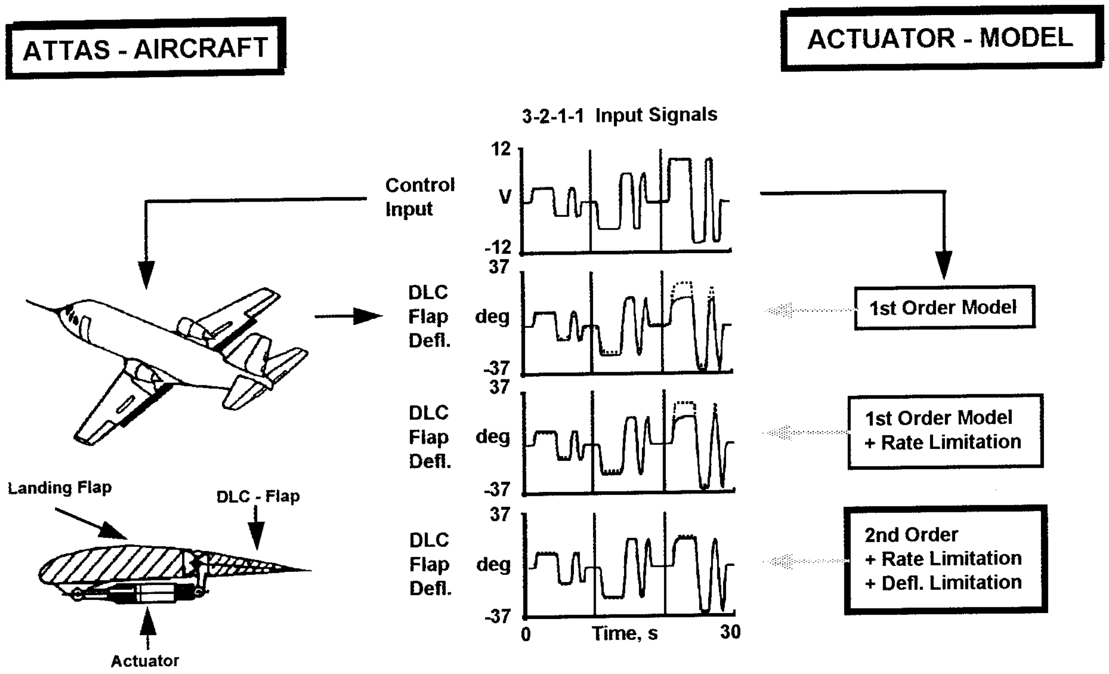

Fig 8: Actuator System Identification

time, there would be a clear responsibility on the aircraft manufacturer for the data package.

So far only modelling issues have been addressed. The other consequence of defining the task to be simulated is that the cues essential to represent the task can also be defined.

4.5 Cue Requirements

In the subtlest cases, in order to determine the cues needed for successful representation of a flight task, an understanding of the physiological and psychological processes involved in carrying out the task is needed. More generally, though, some basic principles apply. There should be a close relationship between the control feel characteristics in the simulator and on the aircraft, and a simulator with a visual system would be expected to provide more cues than one without. The last major cue is the provision of motion to the pilot either through the seat or the cockpit itself. Reference 15 presents details of the closed loop processes taking place during a simulated or actual flying task. In general, motion cues are more important for responses at high frequencies, and visual cues dominate in importance at low frequencies (0.1 Hz). [15]

Within these gross assumptions are many other considerations. For example, the visual cues presented by a low cost visual system presented to the pilot over a small field of view may well provide adequate cues for general handling of an aircraft, but if the scene lacks detail and texture at low altitude it may not provide satisfactory cues for a landing approach - in particular for the flare manoeuvre.

Similarly, a particular motion system may be unable to provide the high frequency cues to represent turbulence adequately unless it has a high enough bandwidth. Views on the need for motion differ although the following guide-lines have been suggested in reference 16.

- To give accurate motion sensations requires high performance and large travel.
- It is better to have no motion than a system which gives false cueing.
- Motion systems are of most importance for representing handling where stability margins are low (i.e. the pilot is stabilising the vehicle), in cueing for failure cases involving a transient response, or cueing the effects of turbulence on flying qualities.
- Small travel motion system can be used with advantage for subjective cueing simply to add realism to the simulation.

More recent experience has also shown that motion can be important to generate the cockpit accelerations arising from the energetic use of control surfaces driven by Active Flight Control systems.

Defining the drive algorithms for a motion system is a task which should be given careful consideration. Much has been published on the subject but broadly speaking the choice of algorithms will probably depend on:-

i the capabilities of the system in terms of number of degrees of freedom, travels and acceleration performance,

ii the type of aircraft to be simulated and

iii the phases of flight which it is intended to represent.

The validation of these cues should initially be an objective one regarding them as independent subsystems within the overall simulation. Tests should be devised which prove that the assumptions made when specifying the cueing required have been realised. For a visual system, the objective is to ensure that the view seen by the pilot is geometrically correct (within the constraints of the visual system hardware) at all times and that the time delay in presenting these cues is known and minimised. An arrangement using a theodolite fixed at the pilot position may be considered necessary for verifying the former.

Motion cues can be validated most satisfactorily by recording signals from accelerometers and other pick-offs which measure the motion close to the pilot's head. This combined with readings taken from a clinometer to ensure static accuracy could be used to ensure that the wash-out algorithms are functioning as intended and that the time delay between demanded and achieved motion are minimal. A full range of suitable tests is described in AGARD AR144[17] and these should be combined with similar tests to evaluate the combined dynamics of both the motion system and the drive algorithms, which include wash out and cross coupling.

The two decision paths in Fig 2 now converge as the simulator is treated as a complete unit. The final objective test before embarking on pilot-in-the-loop assessment is to check that the end-to-end frequency responses and time delays are acceptable when the simulator is operating as a complete system. These responses and delays are a combination of the behaviour of hardware components and software transport delays. Good update rates for software should always be sought, particularly as the trend towards distributed processing means that the flow of data may pass through a number of different processors before affecting the cues sensed by the pilot.

Reference 18 states that "accumulated time delays from a variety of simulator component sources will cause reductions in the effective system bandwidth relative to those in flight. If the bandwidth changes occur in a rating sensitive region, the simulator will be more poorly rated than flight for this reason alone".

4.6 Criteria of Acceptability

Criteria of acceptability depend strongly on the application of the simulator, e.g. if it is used as a training device, as a handling qualities development tool or as a testing tool for real hardware system validation or acceptance.

For piloted simulators the acceptability criteria require that

Task performance

Handling qualities and pilot workload, and

Control activity

are all satisfactory representations of the same characteristics on the aircraft in flight. Unfortunately there are no firm guide-lines on what constitutes a satisfactory representation. The best guidance is given in the documentation that supports handling qualities criteria, and this needs to be combined with sound judgement from experienced simulation engineers, aircraft designers and pilots.

Handling qualities criteria describe the influence of system parameters on pilot assessed handling qualities. These data are given in the MIL-F-8785[4] and the MIL-STD-1797, and the related background information[5]. By using identical methods to extract handling qualities parameters from the simulator, it can formally be shown that the simulator fulfils the required handling quality levels. All these methods cannot replace direct pilot assessment to ensure that the behaviour of the simulator corresponds to that of the aircraft. This is especially true if motion and visual cues are important features of the simulation task.

4.7 Validation methods

4.7.1 *Time domain*

The technique most widely used for simulation validation consists of matching measured time response data from flight tests with the simulated response by using identical control inputs. Typical traces from flight are seen on Fig 9. These are compared with responses from the simulator on Fig 10. The comparison is made by cross-plotting measured and simulated data or by overlaying the plots to identify the agreement and the differences. The allowed error is given by expert judgement (Fig 3). Typical accepted deviations are about 1-10 % as a function of the variable and the application [19].

A pre-requisite for using this technique is that the measurement errors and inaccuracies in the measured data are known and extracted before the comparison is made. Due to the 'open-loop' nature of this method, any incorrect initial values of the model will lead over time

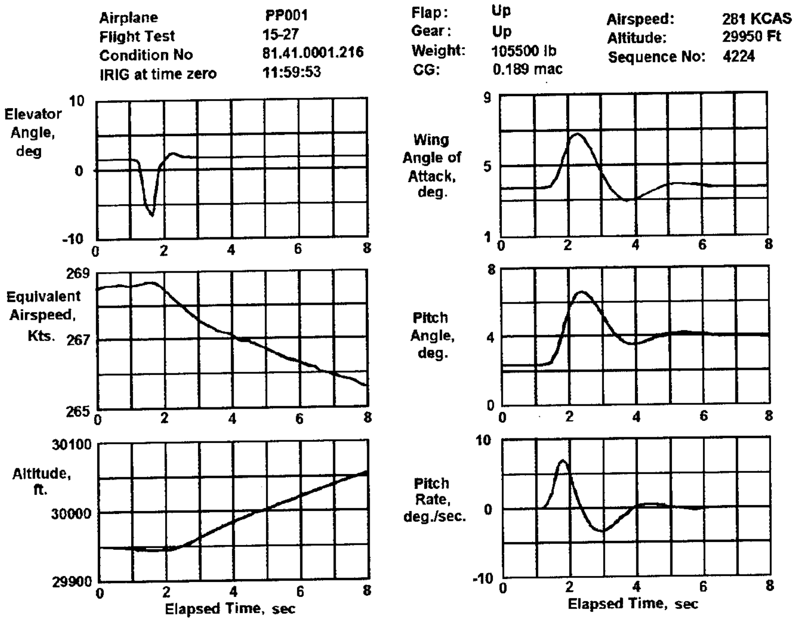

Fig 9: Example of Aircraft response data

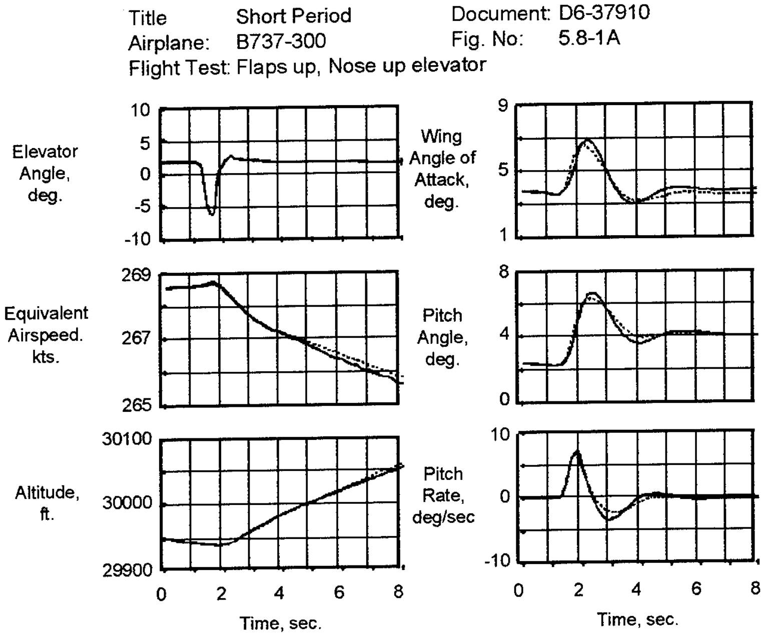

Fig 10: Comparison of Aircraft and Simulator responses

to large discrepancies. To alleviate these difficulties, so called "closed-loop" testing methods have been developed[20,21] so that incorrect initialisation can be identified and corrected. Nevertheless, if discrepancies remain, the main problem is to identify which part or which parameter in the model has to be adjusted, without the risk of changing other dynamic characteristics of the model.

4.7.2 *Frequency domain*

For simulation validation, the comparison with the real world data can also be applied in the frequency domain by comparing frequency response data (e.g. Bode plots). These data are often available, particularly for actuation systems.

Frequency domain methods require the excitation of both the aircraft or subsystems and the simulator by sinusoidal inputs at different frequencies, or by continuously increasing frequencies (sweeps). The frequency response is calculated either by special frequency analysis equipment or by using Fast Fourier Transform methods. The resulting Bode plots of both systems are overlaid and compared visually. Any unacceptable differences in the frequency range of interest can then be noted.

Here again, the problem arises of how the deviations between the two curves have to be weighted, in order to estimate the influence on handling qualities. As a guide, frequency response boundaries of deviations which are unnoticeable to the pilot as far as handling qualities are concerned are given in the MIL-F-8785 Standard Handbook[5]. However, this information is only available for the pitch axis response.

In addition to frequency response comparison, the validation can be made by using the equivalent system approach to calculate the transfer function of the equivalent low order system, and then comparing the estimated transfer function parameters or the calculated frequency response. In order to improve the matching process or to minimise the difference between the frequency responses, automatic parameter identification methods for the frequency domain are available [22].

The main advantage of using frequency response data for simulation validation is that both the phase and high frequency characteristics which are very important for closed loop stability (e.g. PIO-problems) can easily be compared. For instance, frequency response comparison is very useful in motion system validation, to evaluate acceleration response and wash-out characteristics. Compared to the time domain methods, the frequency domain methods require more equipment (hardware and software) for system excitation and data analysis.

4.7.3 *Hardware-in-the-loop*

Typical examples of hardware-in-the-loop simulation are the use of a fully representative simulation cockpit using aircraft hardware to provide the pilot with a real world environment, or the connection of an "iron bird" to the simulation, on which the aircraft's hydraulic and electrical systems, including loaded actuators, are implemented. Hardware-in-the-loop is important if high realism is required, and if the behaviour of the subsystem is too complex to be simulated under real time conditions. In particular, for the simulation of the new generation of aircraft with multiple redundant fly-by-wire flight control systems, real flight control computer hardware is required to be able to represent all functions, modes and the failure behaviour. This is mandatory if the flight control system is to be validated or certified in the simulator.

The big advantage in using real hardware is that no effort is needed for the validation of the functions which are represented by the subsystem. But if simulation is used to validate or certify hardware subsystems, it must be proved that the data communication between subsystem and simulation (e.g. by bus system interfaces like ARINC 429, MIL-BUS 1553B) is identical to the real world. Furthermore, the real-time aircraft simulation data must be synchronised with the hardware and calculated at the same or a multiple of the frame rate of the real-time process of the subsystem.

4.8 **Subjective Assessment**

The final stage of the validation process is to introduce a pilot into the loop, to fly the task defined at the outset. Obviously, the pilot must be familiar with flying the task on the actual aircraft. It is also important that the pilot is subjected to relatively short testing sessions with actual flying interleaved. This reduces the problem of the pilot adapting to the simulator and any deficiencies it may have. Reference 15 contains a rating scale for simulator validity which has been slightly modified to make it independent of flying task and is shown in the Table on the next page. This is a useful addition to the use of Handling Qualities and Workload rating scales such as the Cooper-Harper Handling Qualities[23] and the Bedford Pilot Workload[24] scales.

As well as seeking pilot opinion during an assessment, simulator fidelity can also be verified by observing pilot behaviour during the task. Monitoring the pilot's activities and comparing them with flight activities whilst performing a similar task can either contribute to the validation of a simulator or point to areas where the simulator might be deficient. Confidence in the simulator will be increased if there are no significant differences observed in control activity or instrument scanning strategy. If it is considered that these activities differ significantly from flight experience, then the reasons for these differences should be established, so that no doubt is cast on the use of the simulator for acceptance of the aircraft.

If, at the pilot assessment phase, it is concluded that the simulator replicates the flying task in performance, handling and workload, and in control activity, then the simulator has been validated overall for this chosen task. However, should the subjective assessment highlight deficiencies, some retracing through the process is necessary.

Category	Rating	Adjective	Description
Satisfactory representation of actual vehicle	1	Excellent	Virtually no discrepancies; simulator reproduces actual vehicle characteristics to the best of my memory. Simulator results directly applicable to actual vehicle with high level of confidence.
	2	Good	Very minor discrepancies. The simulator comes close to duplicating actual vehicle characteristics. simulator results in most areas would be applicable to the actual vehicle with confidence.
	3	Fair	Simulator is representative of actual vehicle. Some minor discrepancies are noticeable, but not distracting enough to mask primary characteristics. Simulator trend could be applied to actual vehicle.
Unsatisfactory representation of actual vehicle	4	Fair	Simulator needs work. It has many minor discrepancies which are annoying. Simulator would need some improvement before applying results directly to actual vehicle, but is useful for general handling qualities investigations for this class of aircraft.
	5	Bad	Simulator not representative. Discrepancies exist which prevent actual vehicle characteristics from being recognised. Results obtained here should be considered as unreliable.
	6	Very Bad	Possible simulator malfunction. Wrong sign. Inoperative control(s), other gross discrepancies prevent comparison from even being attempted. No data.

4.9 Deficiencies

Simulator cueing is inevitably deficient to some degree and it is reasonable initially to look in this area for the cause of the deficiency. Motion cues can never fully represent those of the aircraft, visual cues may be restricted in terms of field-of-view or scene detail and both suffer from transport delays. Simulator cues should be completely eliminated from the investigation as the cause of any deficiency before looking elsewhere for the cause. Not only should the investigation consider the validity of the cues provided by the simulator but also any cues which may be missing. This would imply an error at the stage when the necessary cues for the task were defined. In the worst instances this could be as dramatic as concluding that a motion system is needed for a simulator which was originally considered not to require one.

Assuming that cues have been eliminated from the investigation, the next point to consider is whether any simplifying system assumptions made at the outset were appropriate. Subtleties of handling qualities may be missing as a result of a modelling simplification thought to be justified at the time.

5. CERTIFICATION ISSUES

5.1 Scope for Simulation in Civil Aircraft Certification

As discussed in Section 2.1, Airworthiness Requirements for civil aircraft do not specifically state that flight simulation is an acceptable means of demonstrating compliance, nor do they exclude such testing. Paragraph 25.21 of Reference 1, relating to "Proof of Compliance", states

> "(a) Each requirement of this sub-part must be met at each appropriate combination of weight and centre of gravity within the range of loading conditions for which certification is requested. This must be shown by-
>
> (1) tests upon an aeroplane of the type for which the certification is requested, or by calculations based on, and equal in accuracy to, the results of testing: and
>
> (2) systematic investigation of each probable combination of weight and centre of gravity, if compliance cannot be reasonably inferred from combinations investigated."

It can be read from this paragraph that simulation is acceptable if it produces results equal in accuracy to those from flight testing. This interpretation is now widely accepted by both manufacturers and certification authorities, as described in Section 2.1. The division of certification between actual flight testing and simulation comes from a case by case negotiation between the two parties. To justify this approach, the US Department of Transport (FAA Systems Development and Research Service) sponsored a study of the benefits to be gained from the use of simulation in the certification process[25]. The study, co-ordinated by the Lockheed-California

Company, surveyed experience and recommendations from Industry, based on an FAA Advisory Circular[26], taking account of the economic and technical considerations.

Two categories of tests were identified as having potential for the use or expanded use in simulation. The first category, associated with Sub-Part B of Reference 1, is, in the main, related to performance. The tests are

25.105	Takeoff
25.107	Takeoff speeds
25.109	Accelerate-stop distance
25.111	Takeoff path
25.113	Takeoff distance and takeoff run
25.115	Takeoff flight path
25.117	Climb: general
25.119	Landing climb: all-engine-operating
25.121	Climb: one-engine-inoperative
25.123	En-route flight paths
25.125	Landing
25.149	Minimum control speed
25.173	Static longitudinal stability
25.175	Demonstration of static longitudinal stability
25.177	Static directional and lateral stability
25.179	Demonstration of static directional and lateral stability
25.181	Dynamic longitudinal, directional, and lateral stability
25.253	High speed characteristics

Excluded from these tests are those relating to stalling and stall warning.

The second category, associated with Sub-Part F of Reference 1, is related to equipment. The tests are

25.1301	Function and installation
25.1303	Flight and navigation instruments
25.1309	Equipment systems and installations
25.1321	Instruments- Arrangement and visibility
25.1323	Airspeed indicating system
25.1325	Static pressure systems
25.1327	Magnetic direction indicator
25.1329	Automatic pilot system
25.1331	Instruments using a power supply
25.1419	Ice protection
25.1431	Electronic equipment
25.1457	Cockpit voice recorders
25.1459	Flight recorders

Reference 25 also recommends that Sub-Part D tests of Reference 1, relating to flight control and stability augmentation (25.671, 25.672), are suitable candidates for the expansion of simulator usage.

Additionally, the study reports a clear preference from Industry to negotiate the use of simulation in certification on an "individual case" basis. The rationale behind this recommendation is that the question of what constitutes an acceptable simulator is not addressed in the Regulatory Documents. The Industry preferred instead "guide-lines concerning simulator conformity and/or validation, rather than a guide as to what may or may not be simulated."

In 1983/84, the Swedish Aviation Authority (Luftfartwerket) sponsored a study of the "simulators for certification" issue. The areas addressed were

- specific tests suitable for clearance on simulators
- likely benefits, including cost savings
- required standards of simulation.

The initial study[27] was followed by a series of trials on the SF-340 Development Simulator at Saab, Linköping. Test schedules from the SF-340 Flight Certification Programme were repeated on the simulator, using the same techniques and test pilots as used in Certification. 52 test points relating to performance/flying qualities were flown. It was concluded that

> "the recordings obtained from the simulator tie up closely with those obtained from the equivalent flight tests. Also, in most cases, the pilots rated the task difficulty as similar to that experienced in flight. Two test conditions were considered by the pilots as being more difficult than flight. The first was lateral trimming, to measure static stability. The second was flying close to the stall."

Further, it was recommended that

> "the areas where simulators should be considered for Certification are: Avionics, Failure Cases, Performance (take-off and landing), and Handling Qualities - (especially when airplanes are modified)."

In the last ten years, improvements in simulator technology have enhanced the accuracy and realism of simulators, and have extended the areas where valid ground testing is possible. At the same time, extensive use of avionics in civil aircraft has added to the certification task. Much of this additional load is suitable for clearance on simulators.

5.2 Scope for Simulation in Military Aircraft Clearance

Although there is a greater variation between nations in their methods for the specification and clearance of military aircraft, there is usually a clear indication to manufacturers that simulation plays a part in certification. Taking Reference 4 as an example, Chapter 4 states

> "4.1 Compliance Demonstration. Compliance with all requirements of section 3 shall be demonstrated through analysis. In addition, compliance with many of the requirements will be demonstrated by simulation, flight test, or both. The methods for demonstrating compliance shall be established by agreement between the procuring activity and the contractor. Representative flight conditions,

> configurations, external store complements, loading, etc., shall be determined for detailed investigations in order to restrict the number of design and test conditions. The selected design points must be sufficient to allow accurate extrapolation to the other conditions at which the requirements apply.
>
> Table XVIII specifies general guide-lines but the peculiarities of the specific aeroplane design may require additional or alternate test conditions. The required failure analyses shall be thorough, excepting only approved Special Failure States."

(Table XVIII has the title "Design and Test Condition Guide-lines", and relates the requirements to conditions (load factor, altitude, speed, and Phase of Flight) to be tested.)

> "4.1.2 Simulation. The danger, extent or difficulty of flight testing may dictate simulation rather than flight test to evaluate some conditions and events, such as the influence of Severe disturbances, events close to the ground (except 3.2.3.4 shall be demonstrated in flight), combined Failure States and disturbances, etc. In addition, by agreement with the procuring activity, piloted simulation shall be performed before the first flight of a new airplane design in order to demonstrate the suitability of the handling qualities, and also to demonstrate compliance with qualitative requirements in atmospheric disturbances and in the critical conditions identified in 4.1.1.1. *(of Ref.4)* Where simulation is the ultimate method of demonstrating compliance for a requirement, the simulation model shall be validated with flight test data and approved by the procuring activity."

(paragraph 3.2.3.4 relates to longitudinal control in landing)

The difficulty of fight testing all combinations of Table XVIII is further acknowledged in the paragraph quoted below:

> "4.1.3 Flight Test Demonstration. The required flight tests will be defined by operational, technical and safety considerations as decided jointly by the procuring activity, the test agency and the contractor using results from 4.1.1 and 4.1.2 *(of Ref.4)*. It is not expected that flight demonstration of the requirements in Moderate and Severe disturbances will be done unless required by the airplane mission. Some flights can be expected to encounter actual disturbances; then the qualitative requirements would apply if the disturbance intensity could be categorised."

The UK Flying Qualities Requirements[28] are divided into two parts; mandatory requirements, which tend to be qualitative, and advisory information, in Leaflets which contain numerical values. The intention is again to allow negotiation between the vendor and the customer. Leaflet 600/1 states:

> "1.9.3 Compliance with some requirements cannot readily be determined quantitatively by flight testing; for example, some dynamic stability requirements, and requirements related to theoretical turbulence models. In these cases, compliance can be shown by theoretical calculation or simulation, by agreement with the Aeroplane Project Director, provided that the data used is derived as far as possible from flight testing and provided that some back-up qualitative flying is done; for example, some flying must be done in real turbulence."

Certification of U.S. naval aircraft involves the granting of flight clearance and the approval of all required documentation after review by the appropriate authority. In the case of the U.S. Navy, this authority resides at the Naval Air Systems Command (NAVAIRSYSCOM). The Air Vehicle Division (AIR-530) has final responsibility for the aerodynamics, control system, material and structural integrity of the aircraft and for determination of critical conditions of flight.

The Requirements for flight clearance of US Navy aircraft, in addition to documentation and analysis, call for the ground testing of

(1) aircraft and ship compatibility
(2) store separation
(3) ground vibration
(4) electromagnetic effects
(5) wind tunnel models
(6) vibration and acoustic fatigue
(7) static and shock
(8) aircrew restrictive effects per anthropometric accommodation instructions
(9) man-mounted equipment compatibility
(10) escape system compatibility

and the flight testing of

(1) captive carriage of stores
(2) separation of stores
(3) carrier suitability
(4) flutter and divergence
(5) acoustic and vibration environment
(6) performance
(7) handling qualities
(8) loads and stress
(9) engine, transmission and cross shaft performance
(10) aircrew equipment interoperability

Information required to support flight restrictions, envelopes, and limits of safe operation, as well as operational suitability and supportability is derived from extensive tests, inspections, trial and evaluation programs. The sources for this data include:

(1) contractor analyses and ground tests
(2) contractor demonstration tests

(3) development test and evaluations
(4) Board of Inspection and Survey (INSURV) aircraft trials
(5) technical evaluations
(6) operational evaluation (OPEVAL)

Items (1) and (3) are conducted by contractor test engineers and test pilots. Items (4) and (5) involve contractor and Navy test personnel and Item (6) is purely Navy personnel. The complete testing, certification, and OPEVAL process often takes years to accomplish. Flight testing follows a prescribed format, each level opening a larger operational envelope. A typical sequence as followed by the F-14 and F/A-18 aircraft is:

(1) ground check/fault testing
(2) take off and landing
(3) low speed performance/manoeuvrability
(4) high speed performance/manoeuvrability
(5) air refuelling
(6) stores/weapons carriage and separation
(7) aircraft carrier suitability
(8) high angle of attack testing
(9) spin/departure testing

5.3 Economics

The case for greater use of simulation in aircraft certification rests to a large extent on the economies that might ensue. The relative costs of operating development aircraft, and performing equivalent tests on simulators, are needed to support the case.

Many studies have been carried out to compare the relative costs of flying and ground-based simulation when used for crew training. The costs that emerge vary with the size and complexity of the aircraft, and the nature of the training. Also, the basis of the estimates (whether they represent only the direct operating costs, or include factors such as aircraft or simulator depreciation) introduces uncertainties into the comparison. Typically, aircraft operating costs are in the range \$2,000 - \$20,000 per hour. At the top end of the range, the ratio of aircraft to simulator cost is high - 30:1 is typical for aircraft like the Boeing 747. Similar ratios, or even higher, apply to operational training for advanced military aircraft. The ratio reduces to 8:1 for a small jet trainer.

Equivalent figures relating to development flying are not readily available, partly because the basis of the estimate (what overhead costs to include, and which tests to include) is arbitrary. Reference 25, however, does contain costs, and overcomes the difficulty of what overhead costs to include by

> "assuming that
>
> - the cost of the flight test aircraft would not be considered
>
> - the cost of any simulator or capital equipment used would be considered as part of the aircraft development costs.
>
> Items included as flight test costs were fuel, landing fees, insurance, crew, data analysis, and reporting. Items included in simulator costs were personnel, data analysis, and reporting."

On this basis, the cost of a flight test hour for the Lockheed L 1011 (in 1976) was estimated at \$10,000, and the cost of a simulation test hour at \$1,000. Rather surprisingly, the advantage in favour of the simulator was reduced, because it was found that although the tests in the simulator took the same time to perform as the tests in the air, the time in the simulator was longer

> "because of test repetition and/or deviation from the test plan as requested by FAA and/or Company test pilots. Typically a single FAA test pilot is aboard the flight test demonstration, while a great many more may be present for a simulator test. The speed at which changes in configuration may be made on a simulator obviously influences the requests for repeated or special tests by witnesses."

According to Reference 25, the Certification Flight Tests for the L1011 which were suitable for the use or expanded use of simulators required approximately 240 flight test hours (\$2.4M) to demonstrate compliance.

Typically, the certification programme for a new transport aircraft takes 11-12 months from first flight, and involves 1200 flying hours. The qualification for service use of military aircraft is much longer, and is a much more expensive process. The clearance from first flight to service use for an advanced strike aircraft can be as long as four years, and can involve up to nine development aircraft. Between 4000 and 8000 flying hours are needed, and the cost per hour is unlikely to be less than \$20,000. Clearing weapon systems, and proving operational effectiveness, particularly in low level flight, are particularly expensive because of the additional costs of special facilities, such as test areas, ranges and ordnance.

At the same time, the manufacturers of such aircraft will have invested heavily in ground testing, and in particular, in flight simulation. It is therefore likely that the standard of simulation used for aircraft development can be used with little additional cost for flight test support and aircraft clearance. The longer timescales of the flight test programme also ensure that the aerodynamic and systems modelling is supported by early flight test results.

5.4 Simulator Qualification

When an aircraft is offered by a Manufacturer to a Certification/Acceptance Authority for approval, the standard of the aircraft must conform to the standard of the aircraft which will enter service. Correspondingly, the standard of a simulator being offered to the Authority as an alternative means of assessment must be shown to be representative of the aircraft in the respects which relate to the intended tests. The difficulty of legislating the required standard presents a major obstacle to formalising the use of simulators for certification testing. Sections 3 and 4 of this present report present the main technical issues associated with simulator validation.

In the case of civil aircraft certification, a parallel can be drawn between these issues and the formal qualification of a simulator for crew training. It is worthwhile therefore to review the process by which a training simulator is approved.

In the late 1970s, the US FAA introduced their Advanced Simulator Plan. The approval requirements are contained in Reference 26. It is an advisory document which in its introduction explains that it sets out "one means that would be acceptable to the Administrator for the evaluation of airplane simulators....". The Advisory Circular specifies that an Approval Test Guide must be developed. This approval test guide is a comparison of the simulator versus the aeroplane static and dynamic response characteristics. It is a means that the FAA can use to verify that a simulator possesses sufficient fidelity when matched against the aircraft to meet the Phase I, II or III Standards of training outlined in their Advisory Circular.

The ATG not only is required to prove the performance of the simulator against prescribed data but is also required to "describe clearly and distinctly how the simulator will be set up and operated for each test". The use of a driver program to automatically accomplish the tests is encouraged but is not mandatory. Such a driven ATG is known as an Automated or Auto-ATG and previously had to be designed in such a manner that, at any time in the test, the driver can be disconnected and the manoeuvre continued by the pilot, to completion. This requirement has been dropped for simulators evaluated under FAA Advisory Circular AC120-40B[3] and thus back-driving of controls is a matter of choice. The value of an Auto-ATG can only really be appreciated by someone who has tried to manually reproduce the control inputs contained in the check-out data to such a level as to achieve simulator results which match the aircraft from which the data was derived. The task of manually flying these tests is one which takes a fair amount of practice, not to mention skill.

In order to produce an ATG, check-out data is required. The source of such data is closely controlled. Firstly it must be flight test data, except in some limited instances which will be covered shortly. Unless otherwise specified the data should reflect the aeroplane performance at normal operating weights and centres of gravity and must be traceable to a particular aircraft, identified by its tail number or registration, on a particular flight. If the only test carried out is one from an extreme operating configuration it must be balanced by a test conducted at the opposite extreme. The only exceptions to the requirement to use aircraft flown data are to cater for aeroplanes first certificated prior to June 1980, when after reasonable attempts to obtain such data have failed alternative data may be submitted to the FAA for approval together with an explanation of the reason for and the source of the substitution. In the case of an aeroplane not yet certificated some predicted data may be used after the agreement of the FAA but this will, usually, have to be replaced when certificated aircraft data does become available. The use of substitute data has, for example, been approved in the case of the A320 aircraft because of its highly augmented flight controls. Flight manoeuvres which needed to be flown in order to obtain some data for simulation purposes could not be obtained because the aircraft's built in protection devices prevented them from being flown. Accordingly the Regulatory bodies have agreed to the use of engineering data obtained in well defined conditions.

Once Evaluated and Approved, an operator may use the simulator in an approved training program and take advantage of the credits awarded to it by virtue of its Phase of Approval. To maintain this qualification, the simulator will be evaluated on a recurring basis using the currently approved Master ATG. Unless otherwise determined by the FAA, these recurrent evaluations will be accomplished by a Simulator Evaluation Specialist every four months. Scheduled to last no longer than eight hours per inspection, the testing will comprise of one-third of the validation tests in the MATG plus all the Functional tests with the aim of completing the whole of the MATG annually.

In the past two years, an International Working Group under the auspices of the Royal Aeronautical Society has met to develop common standards for simulator approval, so that expensive duplication of tests to satisfy the particular requirements of National Authorities can be avoided. The Group's recommendations[29] have been adopted by ICAO. Criteria are based on the US FAA requirements, as summarised above, and variations from them which appear in the requirements of other Authorities.

The recommendations of the International Working Group provide a sound basis for more detailed developments, which will address the

- type and number of validation tests
- flight conditions for each test
- methods of proving compliance
- objective and subjective testing
- classification of simulators into levels of complexity.

This work will be a good basis for formulating acceptance procedures for simulators intended for aircraft acceptance. It is a daunting task, however, because the standards required are likely to be more severe than those for training simulators. If a training simulator fails to represent the aircraft in some respect, the consequence could be a flaw in pilot training, which might then result in incorrect procedures in flight. But if the certification simulator fails to represent the aircraft, the consequences could be much more serious. An aspect of aircraft behaviour might be wrongly certified, with direct implications for passenger safety. It is to be expected, therefore, that the present arrangement, of case-by-case approval, will continue to apply, and that the number of cases will increase as the capability of modern simulators is recognised.

Formalising the use of simulators to clear military aircraft presents a different challenge. There is no internationally recognised standard for military aircraft training simulators which is equivalent to the one discussed above for civil training. Consequently, there is not an agreed basis for validation and acceptance testing of military simulators. But the drawback of legal liability for passenger safety, if the acceptance procedures are inadequate, does not have the same implications for military aircraft.

It has been shown in Section 5.2 that, because of the scale of testing needed for advanced military aircraft, the case for the use of simulation in acceptance procedures is greater than in the civil case. It has also been shown that the military specifications reflect this need. There is therefore every incentive to encourage the maximum use of simulators in military aircraft clearance. The way ahead is to categorise the flight testing of a typical new aircraft into areas which could, wholly or in part, be transferred to ground-based simulation, given a suitable simulator.

The next task would be to consider the requirements for a simulator for each of these test conditions, in terms of technical performance required from each element. A further consideration would the provision of hard evidence that such testing is equivalent (or better) than conventional flight testing. This aspect is vital, because validation of the simulation has a strong subjective component.

5.5 Other Issues

Special efforts should be applied to advancing the use of simulation in areas where other means of acceptance testing are inadequate or inappropriate and, in particular, where considerations of safety, security and practicality may preclude certification/acceptance based on flight testing. Extreme meteorological conditions (e.g. turbulence or wind shear) cannot be set up on demand in flight. Suitable mathematical models of these phenomena exist and simulation could replace flight trials for this aspect of certification/acceptance now. Trials staged overseas in locations prone to extreme atmospheric conditions are time consuming and expensive. Provided adequate data can be obtained from testing in environmental chambers etc., simulation could also partially or fully replace such trials.

Testing of heavily degraded and limiting failure modes may be unacceptably hazardous or impossible to simulate in flight: e.g. complex failure modes including mechanical failures. Simulation can be applied directly to this aspect of certification/acceptance testing provided the characteristics of the failure modes can be adequately defined from rig or other tests. The challenge here is to identify all the critical failure modes, and this applies equally to simulation or flight based certification/acceptance testing.

Considerations of security, particularly of electromagnetic emissions, cost and practicality will constrain or preclude flight testing to demonstrate operation in complex operational environments. But extensive co-operation with friendly surface and airborne forces (e.g. passing of intelligence and hand-over of targets, integration with battlefield management systems, and effective operation during many-on-many engagements) will be essential capabilities for future combat aircraft. Furthermore, the drive towards procurement of complete weapon systems for a fixed price will place increased emphasis on the need to prove total system operational effectiveness as opposed to demonstrating platform performance characteristics. Such requirements will place heavy demands on the development of sophisticated models of friendly and hostile weapon systems, and on capabilities to network simulators. However, these efforts will be equally applicable to the provision of adequate full mission training simulators for such aircraft, and simulators with these capabilities could also play a significant role in the development of tactics and Operational Assessment.

The strongest thread running through all these requirements is the need for increased sophistication, and scope, of modelling and model validation. This in turn will require extensive data gathering and analysis, improved tools for software development, and improvements in computer hardware and software efficiency. Improvements in other fields of simulation technology (e.g. visual and motion cueing) may be appropriate for some applications (e.g. ultra low level and NOE flight of highly agile aircraft/helicopters and visual resolution to identify targets at extreme range), but in general any shortcomings in the best current systems seem unlikely to be so severe as to preclude the use of simulation for the kinds of testing described above. Nevertheless, the progressive reduction in cost for similar levels of capability must be as welcome in this application as it is for training simulators.

6 CONCLUSIONS

Piloted simulators are already being used as part of the certification or acceptance process for aircraft and, particularly their sub-systems. However, there is currently little, if any, guidance for clearance authorities or manufacturers to ensure that simulators are, and are seen to be, validated effectively. Current practice relies heavily on the subjective opinion of experienced test pilots and, whilst this is an essential part of any validation, it can only be relied upon after rigorous verification of mathematical models and validation of the behaviour of simulation systems has been completed satisfactorily. An appreciation of the effects of simulation systems on the responses of pilots when performing relevant tasks are particularly important. It is in these systems that the 'art' of simulation is used to represent the real visual scenes, motion, sounds, and response of instruments that the pilot uses to identify his situation and determine his actions. In nearly all respects the simulated 'world' cannot respond in exactly the same way as the real world.

A simulator will be satisfactory for clearance activities if there is confidence that any differences in simulator response are so small that pilot response and performance in the relevant clearance task is the same as it will be in flight. Thus a definition of a **valid** simulation for a **given task** is:

> A piloted simulation will be valid for a selected task when the representation by individual components of the simulation and by the complete simulation meets both the quantitative requirements of the manufacturer/authority and the subjective evaluation of pilots with relevant experience such that a manufacturer will confidently present simulation as the sole means of demonstrating compliance with the Authority's certification or acceptance requirements for some element of that task.

The main involvement of simulators in certification at present is in the selection of cases for flight demonstration; in providing opportunities to determine piloting procedures and to practice them before flight tests, and in demonstrations for certifying authorities. However, there are a growing number of examples where simulation has been used as the sole demonstration of particular cases for flight clearance. Examples begin with the NASA/USAF Space Shuttle, where a normal flight development programme was impractical, Appendix B, and more recently include aspects of the Airbus A320 and Fokker F100 airliners, (Appendix A), where certain less critical or very low probability flight control system failures have only been demonstrated in piloted simulation. This also includes rare and extreme meteorological situations that are almost impossible to obtain or represent in flight.

Military examples have been less obvious in the past because it is not practical to have such well defined certification procedures to deal with the multiplicity of configurations, roles and physical environments encountered by a single type of aircraft. However, simulation is used as one means of identifying cases which must be demonstrated in flight from the very wide range of configurations and failures that must be evaluated. Thus piloted, or theoretical, simulation is being used implicitly to clear cases that are not demonstrated in flight.

More recent examples of the use of simulation in the clearance of military aircraft such as the Tornado, AMX, BAe EAP, and F14A are given in Appendix B.

Essential stages in validating a simulator for a clearance task are shown in Fig 2. There are four primary activities

- Model validation
- Cue validation
- Integrated system validation
- Pilot in-the-loop assessment

Modelling and simulation validation is a mainly analytical activity and the most important pre-requisites are

- Good quality sources of modelling data, e.g. wind tunnel, flight test, etc.
- Appropriate independent flight data to test validity in certification task areas, i.e. not the same test data used to derive the model.

In general, manufacturers are unlikely to propose simulation for clearance demonstration unless the aircraft has good modelling data sources. Independent flight data for validation is readily available for civil airliners where training simulators will be an intrinsic part of any sales of aircraft and standards exist defining simulator modelling and certification requirements. For military aircraft there are no standards requiring flight test data for simulator modelling or certification. It will be much less expensive to incorporate data collection for modelling and validation during the initial development flight trials of an aircraft, when similar tests are required for development, than it will be to carry out a separate series of special tests at a later stage. This requires acknowledgement by government aircraft project offices that provision of simulation modelling and validation data is part of an aircraft's development and not a separate simulation procurement activity.

A particularly important part of model validation must be testing of the software for faults. Associated with this is a need for visible and effective software configuration management to ensure that any validated simulation is associated with a unique and properly safeguarded set of software, which must include the simulation operating software as well as specific models. Faulty logic will not necessarily be identified by matching responses to tests at discrete conditions, and yet can be a source of significant illogical discrepancies.

Cue validation is primarily associated with the physiological and cognitive response of pilots to physical stimuli. Thus, although important guide-lines can, and should, be provided to design and assess the probable capabilities of a simulator for given tasks, the effectiveness of the complete system of motion, visual, tactile and aural cues can only be evaluated by the final activity of pilot assessment. However it is important that quantitative measures of the quality, including dynamics, of these cues are available to avoid known problems and to provide a basis for analysing and curing deficiencies identified during pilot assessments.

One particular issue that frequently arises is the necessity, or otherwise, of motion cueing. This is a major part of the general issue of the importance of dynamic cues that the pilot uses for direct control of the aircraft (Section 3.1.1). Any decision not to use motion cues must be approached carefully. The following are particular examples where confidence in validity would be significantly reduced if motion cueing were absent:

- situations where the aircraft with its relevant control system has low or negative stability
- situations where external disturbances or the motion changes caused by failures are abrupt, e.g. engine failure
- aircraft with active control systems where control surface motions are not linearly or simply related to inceptor (e.g. control stick) position.

The last case is important because active control systems can produce unusual motion at the cockpit through attempts to increase control effectiveness or to modify natural cross-coupling from control surface inputs. Control problems can arise from pilots' natural reactions to these cockpit motions that will not be present in the simulator if there are no motion cues.

Evaluation of the integrated model and cueing systems is used to check the overall frequency responses and end-to-end time delays of the system. These need to be satisfactory before the simulator is presented to a pilot for the final stage of validation.

With the pilot in-the-loop the simulator is assessed in three areas

Task performance

Handling qualities and pilot workload, and

Control activity.

Only if the simulator is a satisfactory representation of the aircraft in all three areas can it be accepted as valid for clearance activities.

For pilot assessment the most important requirements are that the pilots are very familiar with the aircraft behaviour in regimes similar to the tasks to be demonstrated, that they are currently flying the aircraft, and that they are trained in the analysis of flight activities, e.g. a qualified test pilot. These requirements are particularly important because it is easy for any experienced pilot to learn to fly a simulator, but only pilots with relevant experience and training can assess the validity of a simulator to represent a particular aircraft and task. The 'currently flying' requirement is particularly important because experienced pilots will quickly adapt to a simulator and will find it difficult to judge the significance of apparent differences without trying similar checks in flight.

Throughout all these validation (and verification) activities there is a need for appropriate criteria for assessing the acceptability of the simulator or one of its components. For model verification it is usual to set deviation limits for output variables of between 1 and 10% depending on the variable and the task. However, there is significant professional judgement required and the process cannot be totally automated. For cueing systems and overall pilot assessment there are no accepted quantitative criteria. However, experienced simulation engineers have a body of knowledge of appropriate 'good practice' for simulating particular tasks. There is a need to codify some of this knowledge for cueing systems. This should lead to the development of accepted criteria and better dissemination of the available knowledge to all simulator engineers.

Only after all the systems have been accepted as suitable for the tasks can a pilot make an overall assessment. It is particularly important that this assessment is reported using rational and generally accepted rating scales such as the overall scale proposed in the Table of Section 4.8 (p.22) and other accepted rating scales for particular parts of the activity, such as the Cooper-Harper scale[23] for Flying qualities, and the Bedford Pilot Workload scale[24].

The legal frameworks for certification of both military and civil aircraft in Europe and N. America accept that simulation may be used for parts of the process and do not stipulate any cases that may not be cleared through simulation. However, each case where a manufacturer proposes to use simulation will be reviewed by the certifying authority and there are no cases where simulation will be automatically accepted.

Studies in the USA (1977)[25] and Sweden (1983)[27] both concluded that simulation was potentially acceptable for most areas of civil aircraft certification with the probable exception of stall and stall warning. This exception is not surprising as modelling of this region is particularly difficult, good motion cueing is essential, and motion systems of that time were unlikely to provide adequate quality. Motion systems and their drive algorithms have improved significantly, but the modelling difficulties still remain. Thus stall demonstration will continue to be a flight case for some considerable time. The other important point to note from the studies is that the Industry prefers "guide-lines concerning simulator conformity and/or validation, rather than a guide as to what may or may not be simulated."

This is particularly important as continuing developments in simulation quality will bring an increasing range of certification tasks within the scope of simulation, and also the simulation systems of different manufacturers will be suitable for different ranges of tasks and vehicles.

The growth of complexity in aircraft systems, military roles, and certification requirements are all increasing the total scope of the certification process. The financial savings available through using simulation instead of flight testing are considerable. Then there are tests in severe weather or of very rare major system failures that must be cleared by simulation as they are almost impossible to test in flight. Surveys have suggested cost ratios for operational training of between 8:1 for a jet trainer to 30:1 for a large transport aircraft per flight hour in favour of simulation. In development flying the cost per flight hour will be much higher, but there will also be a tendency to use the flexibility of the simulator to increase the range of demonstration required by the certifying authority. However, the cost benefits of using a simulator will still be large. Thus it is to be expected that manufacturers and customers will wish to make the maximum possible use of simulation in the certification process.

This means that both manufacturers and certifying authorities require guide-lines and procedures for assessing and demonstrating simulation validity.

Structured guide-lines and requirements for simulation quality in existence at present are the FAA requirements for civil flight training simulators and flight training devices[3]. An important feature of these regulations is the requirement for generating an Approval Test Guide (ATG). This includes comparisons of the simulator responses with independent flight test data, and must "describe clearly and distinctly how the simulator will be set up and operated for each test". This ATG, together with an assessment by an FAA pilot, is the means by which training simulators gain approval (and annual recertification) to replace certain flight training activities. The highest level allows a pilot to convert to a new aircraft type without any flight experience on the new aircraft before his first revenue flight. This requirement for a Test Guide is also a key feature of the recent International Standard for the Qualification of Airplane Flight Simulators[29] presented to the International Civil Aviation Organisation in 1992 by an International Working Group of the UK Royal Aeronautical Society.

These procedures for civil training simulators provide a sound basis for developing assessment methods to qualify simulators for flight clearance demonstrations.

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Appendix A

EXAMPLES OF THE USE OF SIMULATION IN THE CERTIFICATION OF CIVIL TRANSPORT AIRCRAFT SYSTEMS

A.1 USE OF SIMULATION FOR AIRBUS A320 CERTIFICATION

A320 development and certification have made wide use of simulators. These simulators were used for various tasks, such as flight control law definition, cockpit ergonomics and man-machine interface studies, equipment integration, initial training of flight test crews, validation of equipment modifications, analysis of failure cases and responses to atmospheric disturbances. They have greatly enhanced the productivity and safety of the flight tests and have provided an ideal complementary test facility.

A.1.1 Development Simulators

A specific tool was created by Aerospatiale in 1977, to support aircraft Research and Development, named EPOPEE (Etude Prospective pour l'Organisation d'un Poste d'Equipage Ergonomique). The EPOPEE simulator, a fixed-based simulator with visual system, is still used in the area of cockpit ergonomics and man-machine interface. Its specific contribution to the A320 included such important items as the selection of large 7.25" EFIS displays with side-by-side location for the Primary Flight Displays and Navigation Displays, the design of engine parameter presentations on ECAM displays, sidestick and armrest design and determination of the basic characteristics of the C* law selected for pitch control.

Additionally, five simulators were used by Aerospatiale for the specific development of the A320 airplane. All are of the fixed base type. The first one was an A300-B2 type simulator, aimed at integrating and checking the special autopilot computer modified to embody the A320 type control laws and fitted on A300 SN3. These flight test trials allowed a validation of the control law principles, especially in the areas of flight envelope protection and lateral control laws. The role of the simulator was to interface with the real modified autopilot computer in addition to the final tuning of the control laws with a pilot in the loop. It was also used on a systematic basis before any new computer box was flight tested.

A.1.2 Flight Control System and Autopilot Development

Simulator testing of new experimental versions of a flight control computer before fitting it on actual aircraft has greatly increased both effectiveness and safety of the flight tests. As soon as comprehensive A320 aerodynamic data was available from wind tunnel tests, work on the precise definition of the control laws, with gains pertinent to A320 predicted characteristics, was initiated with the help of the "A320 development simulator". This was a fixed-base simulator with a visual system and cockpit arrangement fully representative of A320 design as well as, of course, aerodynamic, propulsive and ground handling models. As computers were not yet available, flight control laws were represented through simulator software.

It is on this development simulator that all the control laws were actually defined in a joint process involving pilots and engineers, and then specified to the computer software teams. This phase also addressed the reconfigured control laws that have to be activated in failure cases.

The quality of the aerodynamic model, and that of the general representation of the whole development simulator, was such that these control laws were not significantly affected during the subsequent phases of aircraft development through to production standard. Pitch laws were kept virtually unchanged for most of the flight phases while lateral law gains were tuned in a reasonable band. The control law architecture was not modified.

A.1.3 Flight Control System Clearance

The next stage was the entry into service, about one year before first flight, of so-called "integration" simulators S1, S2 and S3 which in fact phased out the "development" simulator from which they mainly differ by the use of actual aircraft "black boxes".

All three simulators are fixed-base, and S1 and S2 share a common visual system that can be alternatively connected to one or the other. In addition, S1 may be connected to the "Iron Bird" with an actual replica of the aircraft electrical and hydraulic systems, as well as all the flight control servo jacks. S3 is more specifically dedicated to FMS activities.

The first use of the integration simulator was to check all aircraft computers as soon as the first sets were released by the vendors and to integrate them in an environment fully representative of the actual aircraft. This was really the first opportunity to comprehensively verify the computer interfacing and all logic and monitoring that have to be added to the control laws to make a complete flight control computer. This integration activity was not limited to flight control, but also was used for the autopilot, flight warning, instruments, slats/flaps control, braking and steering.

During the year preceding first flight, future A320 test pilots were given the opportunity to get accustomed to the A320 handling characteristics, so that integration simulators also played an effective training role. After first flight, simulators were systematically used to check the performance of new computer software or hardware before flight test. A comprehensive simulator test program was used to specifically evaluate modifications. This lead to a more safe and productive flight test program.

A.1.4 Failures

Another area where the simulators have also been used extensively is for the assessment of failure cases, both in the development phase but mainly in the certification process. The simulator has proved to be particularly suited to this purpose because:

1) It makes it possible to simulate failures that are very difficult to obtain in flight (such as ADC/IRS parameter drift, radio-altimeter failures, and mechanical failures).

2) It provides time to analyse the warnings and procedures, to reproduce the tests as many times as required, and to cover a wider spectrum of flight conditions.

3) It avoids exposing the aircraft (and lives) to high risk conditions such as double failures, or very remote failure states which would be dangerous if encountered for the first time in flight.

Finally, ground based simulators have also been used to reproduce controlled meteorological conditions that are otherwise difficult to get from mother nature when required. This applies to the simulation of turbulence, associated or not with failure cases, and to the simulation of wind shear.

A.1.5 Simulator Standards

In order to perform all the above mentioned tasks properly, and get credit for the use of simulators for certification, a high level of representation has been sought. For example, aerodynamic, engine, and ground math models are identical to these delivered to training simulator manufacturers, as they are under the responsibility of the same teams who continuously updated the models as soon as flight tests results were available for identification. The visual system is a commercial, up to date type available for training simulators. Additionally, integration simulators are equipped with comprehensive parameter recording and display facilities, as well as specific software or hardware equipment to generate all the required failures.

A.2 USE OF SIMULATION FOR FOKKER F100 CERTIFICATION

A.2.1 Electronic Flight Instrument System (EFIS)

In the development of the EFIS format for new aircraft (Fokker 100, Airbus A-310, A-320, Boeing 747-400), simulation has played an important role. Several simulation devices, ranging from static graphics devices to dynamic graphics work stations are being used in this process. As part of an approved certification programme to demonstrate adequate and representative pilot exposure to the proposed Fokker 100 EFIS Primary Flight Display format, quite extensive flight simulation programmes have been performed using both the Fokker fixed-base, single-pilot, engineering simulator with actual avionics hardware in the loop and the NLR general purpose moving-base flight simulator equipped with Fokker 100 EFIS displays.

A.2.2 Multi-Function Display System/Flight Warning System (MFDS/FWS)

Many certification sessions have been carried out on the fixed-base engineering simulator of Fokker to evaluate the functioning of the MFDS/FWS of the Fokker 100. In the certification pilot's report the following was concluded: "The simulator evaluation has been essential as a certification tool for MFDS/FWS. Ideally, much more effort should be spent in an investigation like this on highly sophisticated and complex interacting avionic systems. Tests on the one hand helped to validate various assumptions on paper, and on the other hand showed problems that were not expected before."

A.2.3 Autopilot

The performance of the Automatic Flight Control and Augmentation System (AFCAS) of the Fokker 100 has been tested in extensive piloted and non-piloted simulation exercises. So-called "pallet tests" have been performed in which a Fokker 100 prototype was used as a ground-based simulator by interfacing it with a simulated set of sensors. The main purpose of this "iron bird like" setup was to efficiently test the behaviour of the AFCAS system under (risky) sensor failure conditions. Of course, because much information on EFIS is so closely connected to the autopilot system, the simulator tests for EFIS certification evoked many comments related to autopilot behaviour and thus can be considered as contributions to autopilot certification, even if it were only for providing certification pilots with system familiarization time before certification flights.

A.2.4 Autoland

The proof that the performance of an autoland system meets the requirement of the category for which certification is requested has to be given by a fast-time simulation in which a large number of factors influencing the autoland performance are varied in a random manner. However, before this simulation starts, the simulation facility (hardware and software) has to be validated. In the Fokker 100 programme approximately 160 actual automatic landings were performed for this purpose. A programme of fast-time simulations and statistical comparisons between flight test results and simulation results has served to validate the simulation program.

A.2.5 Electronic and Hydraulic Control Systems

For the Fokker 100, the influence of failures in electronic and hydraulic systems on flying qualities always has been tested first in a flight simulator and in many cases (control surface jamming), verification has been performed in real flight. However, low probability risky occurrences like flight control jams or disconnects, thrust reverser deployment in-flight, stick pusher activation in combination with wind shear are examples that are suitable for simulation. An interesting example of different requirements being imposed by different authorities is that, for Fokker 100, the effect of in-flight thrust reverser deployment had to be demonstrated in real flight, where for Airbus A-320 the joint French/British/German/Dutch Authorities have accepted demonstration by simulation.

A.2.6 Flight Management System (FMS)

This is an example of a system that received extensive testing in dedicated system integration facilities and piloted fixed-base flight simulator tests during the development phase. In this phase the format of the information on EFIS, the functioning of the system and the assessment of failures in the system were extensively assessed by certification pilots. Final system acceptance was performed in real flight. The fact that simulation facilitated the familiarisation of the certification test pilots with all aspects of the system before the actual certification flights, has reduced the number of certification flight hours considerably.

A.3 SIMULATION FOR CERTIFICATION OF THE ANGLO/FRENCH CONCORDE

NASA simulation facilities were used to address the landing and take-off performance criteria for supersonic transport operation. The work specifically considered the Anglo/French Concorde, which at that time was well on the way to its first flight. Over a three-year period, the simulation was used by teams of engineers and pilots from the U.S., British, and French airworthiness authorities, with support of similar teams from the French and British manufacturers. These latter groups were particularly interested in establishing the validity of the simulation, especially to avoid misrepresentation of the aircraft's performance and handling qualities. Aerodynamic, propulsion, and control system data of a particularly comprehensive nature were made available for the initial simulation and, as flight tests began, data updating and subjective assessments by pilots who had flown the aircraft combined to create a high level of confidence in the validity of the simulation. It was obvious that the quality of the visual simulation system and the large-amplitude cockpit motion were important to the success of the simulation; however, it was appreciated by all involved that the success of the simulator exercises was in large part due to the continuity of individual participation of engineers and pilots over nearly a three-year period. This fostered mutual understanding of the objectives, and the development of skills in the use of simulation. The project provided more strong evidence that pilots must be given the time to accommodate to the irreducible differences between simulator and flight, and that familiarization with unusual aircraft characteristics can be expected to require more time than in flight. Thus, validity of the simulation is dependent upon the evaluation pilot's experience with the tool.

A.4 WIND-SHEAR GUIDANCE SYSTEM CERTIFICATION

In the past several years, simulators have been used in the certification of warning and guidance systems designed to assist the pilot in encounters with severe wind-shear conditions. Since their critical function is in an extremely rare (but extremely dangerous) environment, simulation offers the only practical means to demonstrate performance. In this case, the quality of the aircraft modeling is not of as much concern as the quality of sensor and environment modeling, although there must be some confidence in the modeling of aircraft response to the severe environments. Of course, the flight hardware is used in the final simulator evaluations. Again, the certifying authorities are requiring documentation of initial operational experience with the systems in attempts to verify the simulation experiences.

A.5 HEAD-UP DISPLAY CERTIFICATION

In 1986, a head-up flight guidance display system (HUD), utilizing conformal "flight path" symbology, was certificated for use in manual "CAT IIIa" landings in the 727-100 aircraft. This certification permits manual operation in visibility that require automatic landing with conventional cockpit guidance displays. Recognizing that piloted tests to obtain landing performance data of a statistical nature, of the scope obtained in non-real-time simulation of automatic-landing systems, would be impractical, the certifying authorities accepted more limited data from piloted simulation in the determination of basic landing performance envelopes. These data were then verified in relatively limited flight tests, including some under the actual low-visibility conditions. The developmental testing of the system had been conducted in a Boeing Company engineering development simulator considered to be well verified in a 727 configuration. The certification exercises were conducted in this same simulator using the flight HUD hardware and software. Important in these simulator tests was the availability of a day or night visual simulation system with which realistic low-visibility conditions could be presented. More recently, the process has been repeated for the 727-200 aircraft in preparation for utilization of the system in twenty of the aircraft operated by a US airline. In this case, initial manual operation in CAT II is approved, with the expectation of further certification to the lower visibility of CAT IIIa, or beyond, as operational experience grows.

Appendix B

EXAMPLES OF THE USE OF SIMULATION IN THE CERTIFICATION/ACCEPTANCE OF MILITARY AIRCRAFT SYSTEMS

B.1 ACCEPTANCE TESTING OF SPACE SHUTTLE LANDING CONTROL SYSTEMS

Long before the first orbital flight, a number of non-real-time computer simulations and piloted simulations were contributing to the vehicle's development. The control systems and navigation systems sub-contractors could do their basic development work with non-piloted simulations, but Rockwell, and NASA at the project headquarters at Johnson Space Center, employed a mix of piloted simulators for integrated systems development and testing. Some of these used elements of flight hardware. In the process of verifying the selection of the basic control modes for approach and landing, in 1975, the piloted simulation research facilities at NASA's Ames Research Center were employed. Since that time, Ames facilities have been used in support of Shuttle landing systems' development and acceptance on a regular basis. On several occasions, an in-flight simulator, the Calspan TIFS aircraft, was flown in simulation of Shuttle landings. Experiences with several of these simulations are recounted in the following paragraphs as examples of relatively successful use of the medium.

B.1.1. Configuration Control.

It was obvious that simulation model configuration control and verification across this mix of facilities were required. Basic sources for the aerodynamic model, the control and navigations systems models, and the atmospheric and environmental models were identified. These sources implemented the necessary updates to the models as flight data was obtained, and provided the library of static and dynamic check cases to be used in the re-verification of all of the simulations.

B.1.2. Basic Control System Assessments.

Rate-command roll and pitch systems were chosen and tuned on the basis of fixed-cockpit simulation. Further acceptance tests were conducted in an Ames simulation, which at that time incorporated large-amplitude lateral motion but very modest vertical motion. Cockpit motion exposed an unacceptable lateral lurching that accompanied roll control inputs, the result of an overly "tight" roll-rate command system and a pilot location well above the roll axis. A significant increase in the roll-response time constant alleviated the problem without otherwise degrading lateral handling qualities. The pitch-rate command mode was unfamiliar for flare and landing, and the geometry and mass distribution of the vehicle combined to produce an unusual lagged heave response to pitch. With familiarization, the pilots were able to demonstrate precise touch-downs with a pitch-control technique characterized by intermittent pulsing of the hand controller. In the formal evaluations, the pitch control system was assessed as satisfactory for the glide flight tests; however, in less formal flying of the simulation in off-nominal flare trajectories, several brief encounters with pitch PIO (pilot-induced oscillation) were noted. These events were not seriously considered by the primary evaluators, who tended to attribute them to the inadequacies of simulation and inappropriate piloting technique. On the fifth test flight from the 747, as the pilot was attempting a precision touch-down on the runway instead of the relatively limitless dry-lake bed, he found himself in a serious PIO that terminated only when he removed his hand briefly from the controller. Born was a new objective; develop and test control system modifications aimed at eliminating PIO tendencies.

B.1.3 PIO Suppression.

For this effort, two unique simulation facilities were employed. At Ames, the new Vertical Motion Simulator (VMS) offered large amplitude vertical cockpit motion (16 meters), increasing the fidelity of the simulation of longitudinal maneuvers; and the TIFS aircraft was brought into the study. These facilities were used to evaluate the effectiveness of practical, rather modest control system software modifications. One concept that was retained was a "PIO-suppressor" logic which, upon identifying the onset of large cyclic controller inputs, reduced the effective output gain from the controller to prevent further amplification of the vehicle motion.

Simulation studies of the Shuttle longitudinal control system were given high priority during this period and through the years of the early orbital test flights, and confidence in the control systems, and the simulation assessment procedures, increased. However, some basic truths about the use of piloted simulation were demonstrated. The difficulty of simulating PIO control problems is discussed in Section 3.1.1.2 of this paper.

B.1.4. Auto-land System Verification and Acceptance.

From the initial concept, the Shuttle navigation and control systems were to include an automatic-landing mode; however, its eventual utilization as the primary mode of flight was a matter of controversy between project management and crew. As with all automatic systems, the primary simulation efforts were non-real-time computer studies of performance in the imaginable ranges of environments and component performance. The role of piloted simulation in acceptance was limited to two issues; definition of pilot-acceptable levels of degraded performance of the critical sensors, and pilot capabilities to gracefully revert to manual control in the event of automatic-landing system failures at critical points in the landing trajectory. These verification efforts in ground-based simulation were complemented by experiences with brief engagements of the system during recoveries from the early orbital flights, and some work with the Shuttle Training Aircraft (STA). But, of course, it was only in the ground-based simulator that the necessary breadth of combinations of system failures and flight conditions could be presented to the pilot. Pilot acceptance of the simulation of the landing task as valid for this type of assessment was a basic requirement. Fortunately, experience in the early orbital flights helped to confirm that the motion and visual cueing capabilities in the VMS facility were providing an effective representation of the Shuttle landing task. The pilots concluded their assessments with the recommendation that the automatic-landing system should not be certified, not because of marginal performance, but because they felt that the final flare trajectory and the characteristics of the manual pitch control system combined to present an unacceptable level of risk with even the modest transients experienced at reversion to manual control. Their conclusions also reflected their concerns regarding possible degraded pilot performance following the rigors of orbital flight and high-g re-entry.

B.1.5. Steering and Braking.

During the past four years, most of the piloted Shuttle simulation conducted at Ames have been devoted to a study of the problems of control on the runway from touchdown to final stop. If the Shuttle is to use the runway at Kennedy Space Center, it must be able to deal with the possibility of significant crosswind, and to cope with tire, brake or nose-wheel steering failures. The economics of space flight dictate that the landing gear systems be kept to a minimum weight, and thus to minimum performance margins. Concerns regarding the landing-gear systems were amplified by incidents seen in the first runway landings, and it was decided that the dry lake bed at Edwards AFB, where cross-wind landings could be avoided, would remain the site of Shuttle landings until the steering and braking systems could be improved and certified.

The validity of the VMS simulation of the piloted landing through normal touchdown and de-rotation was accepted, but it was recognized that the representation of steering and braking tasks, particularly with simulated nose-wheel steering or tire failures, was completely dependent upon the accuracy of the modelling of the tire side-force characteristics. During the course of the simulations, doubt regarding the tire modelling prompted extensive measurements of Shuttle tire characteristics on the NASA-Langley test track. The new data significantly changed the behavior of the simulated vehicle in critical scenarios. The simulations provided a wealth of data regarding tire and braking loads as they are affected by the wind environment, failure modes and pilot technique, and lead to the conclusion that the modified systems are adequate for cross-wind landings on the runway. Final certification of the system modifications is being sought by analysis of data from the first flights in the resumed series. If the results are as expected, landings at Kennedy Space Center will be resumed.

B.2 CLEARANCE TESTING OF PANAVIA TORNADO

A brief survey is given below of the main simulation activities concerning certification, acceptance testing and validation during the development of Tornado. Simulation means in this case "manned simulation" with pilots or simulation engineers testing in real-time. The main items are:

- simulation for flight control system development,
- simulation for flight mechanics work, and
- autopilot and terrain-following simulation.

During the development phase of the Tornado weapon system, extended simulations were carried out at MBB for the definition and optimization of subsystems, integration and ground testing of systems and flight test support. Three main factors determined the simulation work:

- MBB's main responsibility for the control and stability augmentation system (CSAS)
- Main responsibility for the basic autopilot modes and at a later stage for the complete autopilot
- Main responsibility for terrain-following flight testing.

Validation of the simulation was performed mainly by comparing simulation results with partner companies and suppliers. A special validation procedure was conducted for the safety-critical flight phase of terrain following.

At the start of Tornado development, all systems were modelled in the simulation computer. A flight control rig and an avionic rig containing real aircraft hardware were coupled later with the simulation. Investigations where hardware rigs are coupled with simulators increase the complexity but also increase confidence in the results.

B.2.1 Flight control System.

Investigation into failure behaviour and switch-over transients is one of the most important fields of simulation. When flight testing has started, the risk of testing failure cases in flight strongly supports the extensive use of ground-based simulation, especially in coupled simulation with the flight control rig. Some examples of failure simulations are:

- CSAS failures and switch-over to reduced modes.
- Engine failure with maximum oil flow reduction.
- Failure of a control surface or actuator.

Acceptance testing of the complete flight control system hardware included a "confidence test" to prove the lifetime of the system components and to improve the confidence level when preparing the flight tests. A typical one hour flight containing various manoeuvres was simulated on the flight control rig and recorded on tape. Then the systems on the rig were stimulated several hundred times with the recorded signals and parameters. The total testing time on the rig had to be considerably longer than the total flight time of the test aircraft.

B.2.2 Flight Mechanics.

Handling quality assessment was supported by simulation flights over the entire flight envelope, which rapidly indicated problems and shortcomings which had to be improved. This procedure was repeated for all critical store configurations. Where the specification required "acceptable" handling qualities without mathematical definition, simulation was the only means of proving the requirement prior to flight testing. Glide path stability during approach, touch-down, landing and ground roll were investigated with and without cross-wind and gusts. Ground roll with thrust reverse required the development of a nose wheel steering augmentation system using simulation facilities extensively.

B.2.3 Autopilot/Terrain-Following System.

The simulation work on the Autopilot and on the Terrain-Following System mainly concerned failure investigations and harmonisation with the other parts of the system, such as the CSAS and the electric and hydraulic systems. A survey of this work is given in reference 30.

The certification of the terrain following system was performed in close cooperation between flight test and simulation departments. It is difficult and time-consuming to define the proper flight path of a TF flight. Therefore a detailed comparison between one flight and a corresponding simulation flight was performed. The two flight paths were matched until relatively small and explicable differences were reached[31].

Simulation flights over various flight test terrains proved that the required criteria in the specification were met, such as peak performance, clearance height error, maximum undershoot, safety factor and so on. For TF performance evaluation, simulation is considered as the adequate reference. When preparing flight testing, flight clearances had to be reached in extended tests and also in simulation tests, mainly in conjunction with the flight control rig and avionic rig. Autopilot and terrain-following flight testing is safety-critical, and a special company based qualification procedure gave confidence as regards the correctness of the rig simulation[32].

B.3 USE OF SIMULATION FOR ACCEPTANCE TESTING OF DASSAULT/DORNIER ALPHA JET

A brief survey is given below of the main activities concerning acceptance testing and validation during the development of Alpha Jet.

The Alpha Jet was specified as a training aircraft and had therefore - with the exception of a yaw damper - a very conventional control system. It was developed in collaboration between Aviation Marcel Dassault/Breguet Aviation, France and Dornier, Germany. Here only the simulation work at Dornier is described.

For certification/acceptance testing, simulation at Dornier was used for special topics in flight mechanics and as support for the flight tests. The simulation facility used was a fixed based operation flight and tactics simulator which is now used for development and training of air-to-surface and air-to-air missions. During the development of the aircraft the simulation equipment was often used without a pilot in the loop, but with stylised control inputs and/or with a 'paper' pilot.

The main simulator tests concerned roll coupling effects. In many simulation runs through the whole flight envelope it was demonstrated that there were no problems at all caused by roll coupling effects. This had to be proved before flight tests with the real aircraft started.

Another group of certification tests using simulation concerned the usual problems in flight dynamics which could not be handled with linearised equations, that is problems where the theory of small disturbances cannot be applied. For the Alpha Jet, there were simulations to examine

- engine failure
- longitudinal dynamic behaviour.

In these, the simulated aircraft was controlled by a 'paper' pilot. The engine failure investigations had to prove that transient behaviour could be handled by a trainee pilot.

The simulations concerning longitudinal dynamic behaviour had to prove that there are no difficulties for a trainee pilot with changes in pitching moment due to landing flaps and/or changes in engine power.

Furthermore, simulation was used to support the Alpha Jet flight testing. An important aspect of this work was to ensure that the simulator and the aircraft had the same behaviour. A "certification" of the mathematical model was obtained which could then be used in the training simulators.

B.4 AERITALIA/AEROMACCHI AMX VALIDATION

B.4.1 Clearance at High Incidence

After an initial effort to evaluate the vertical wind tunnel results through an assessment in the flight simulator, a few flights were conducted to ascertain the aircraft responses from high alpha, through a transition phase, into the departure and spin.

While vertical tunnel data are of good value to assess aircraft responses in a developed spin, after the departure, they are of little value to investigate the initial departure phase. Therefore the first batch of flights were done principally to investigate this phase more thoroughly. Once enough confidence was achieved and enough time had been spent in the simulator by the project pilots to gain familiarity with aircraft responses and to ascertain that the simulator standard was close enough to the aircraft behaviour, a further step was taken. Manoeuvres involving high alpha, high beta, departures and recoveries were assessed thoroughly in the simulator and repeated, step by step, in the air.

This led to a situation in which actual flight data were continuously fed into the simulator model and allowed an even deeper understanding of the flight mechanics involved in the AMX spin characteristics to be obtained.

The evaluation of motion cross-coupling, and the alpha, beta and roll dynamic interchanges, were assessed for tens of seconds, thus allowing fully developed spins to be flown safely. When the benign situation of the basic configuration was completely known, a more demanding phase, from the point of view of simulation and prediction, was initiated. This phase is related to the external stores configurations.

The first effort was to determine significant external store configurations, so that test results from a minimum number of configuration would be enough to assess the totality of combinations. In this context, a real problem was found, during preliminary simulation assessment, for some asymmetric configurations: if pro spin controls were held for a sufficient time (10-20 sec) the dynamics would bring the aircraft into a flat spin with extremely high yaw rates: a practically non-recoverable situation. When this was discovered, special flight tests were used to collect specific data to further refine the model.

Simulation still shows a potentially dangerous situation if the aircraft is allowed to get into a flat spin. But enough was learnt in the simulation to allow a deeper in-flight evaluation and, possibly, to pursue modifications of the FCS and/or store configurations to obtain a departure proof aircraft, or at least spin resistance in ALL configurations. In any case, the results of this testing have been so encouraging that it has been decided that simulation will be used for clearing the two seater version of AMX to perform deliberate spinning.

The process of validation, as it stands today, foresees a limited number of flights, and attention to obtain good matching with simulation. From this point, all assessment and validation will be done in the simulator, with only a few selected departures/spin manoeuvres reassessed in flight.

This use of the simulator can be considered a proof of concept attempt to obtain certification through simulation: if it can be done for high alphas, and departure and spinning of an aircraft, it can be applied to any other field.

B.4.2 Air Brake Development

This example is related to the unusual air brake configuration (for a fighter aircraft), in which the surfaces are used also for lift dumping. Their actuation caused a pronounced nose down trim change, and this was unacceptable from an operational point of view (formation flight, low level flying, etc).

It was therefore decided to compensate this behaviour by automatic scheduling of the stabilator. The scheduling was designed to maintain a straight trajectory after airbrake actuation and this required the incidence to be increased by between 1 and 3 degrees. Simulation showed that this attitude change could be unacceptable if done in an open loop situation. Also, the immediate decreasing of airspeed caused a natural nose down tendency, and this seemed to be objectionable. Before going on and introducing the software change (and the ensuing validation process, lasting 7-10 months), a series of simulation tasks were defined, especially to ascertain the acceptability of the closed loop case.

Close formation flying on a very detailed aircraft model was done on the simulator, because this was thought to be the most demanding operational task as far as trim change was concerned. Formation flight was not only simulated on aircraft of the same type as the one tested, but also on different tactical aircraft models. It was found that the closed loop case was fully acceptable throughout the operational flight envelope.

The customers' assessment of the modification (OTC pilots) was not so favourable. However, the findings of the in-house evaluation were thought to be good enough to proceed with the changes in FCS software. Subsequent flight test confirmed the effectiveness of the modification and also gained approval from customers. It was found that insufficient familiarity with the real aircraft response, and insufficient knowledge of the simulator, caused the different judgements of these changes.

B.4.3 Gun Effectiveness

This example shows a situation in which the FCS software changes developed in the simulator were accepted both during the in-house and customer evaluations. Flight tests on the aircraft showed that the asymmetric position of the gun in the nose caused an unwanted horizontal dispersal of burst during strafing. Traces of actual flight tests were assessed and a modification to the FCS corrected this problem via automatic rudder inputs. Before any flight verification, this modification has been accepted by company and OTC crews through simulator evaluation.

The behaviour of the aiming dot, which accurately represents the bullets' impact point through a very sophisticated fire control system, showed exactly the problem encountered during actual flight test and its solution through FCS software modification. This proved sufficient not only to validate the effectiveness of modification, but also to gain approval of OTC crew, and therefore official customer acceptance of the gun aiming system, even before flight tests were completed. The reasons of this very favourable, but different, result were assessed: it was discovered that the flight experience accumulated during the gap between the two studies had been sufficient for the OTC crew to fully realise the validity of the simulation.

Achievements of this type are dependent on the accuracy of the process of validation of the piloted simulator system. A thoroughly validated simulation system gives the possibility to discover unexpected responses throughout the full flight envelope.

B.5 DESIGN, DEVELOPMENT, AND CLEARANCE OF BAe EAP

The British Aerospace Experimental Aircraft Programme (EAP) is a technology demonstrator aircraft which features an unstable aircraft configuration augmented by Active Control Technology to achieve satisfactory flying characteristics. The development simulator facilities at British Aerospace's Warton plant have been used throughout the development and clearance process of the digital fly-by-wire flight control system. Initial fundamental design work was carried out off-line. Very early in the programme, however, it was essential to carry out pilot assessment of the proposed aircraft handling characteristics.

B.5.1 Origin of aerodynamic data.

Since this was a new aircraft configuration, aerodynamic data originated from wind tunnel testing, as well as analytical work. These were combined to produce a definitive dataset which covered the flight envelope of the aircraft. Non-real-time simulations were constructed on a mainframe computer, to allow frequency response and time history plots to be produced off-line to assist the design work.

B.5.2 Origin of Flight Control System Data.

Design studies using the non-real-time model produced the FCS definition which, for integrity and convenience reasons, takes the form of Fortran code although this is not the language used in the airborne computers. Interfaces to this code and operating constraints were also defined.

B.5.3 Implementation for Real-time Simulation.

The off-line facilities mentioned above are subject to their own independent quality audit procedure. The man-in-the-loop simulator basically requires a real-time version of these facilities. To achieve this, some reworking of the aerodynamic data is required. This is a rearrangement of data into more convenient groups, based on fixed flight conditions, which can then be interpolated in real-time. Further, data is often rearranged into regular grids, the general objective being to pre-process data as far as possible thereby alleviating the run-time computing task. The software which uses this data is different from that used for off-line design studies and has evolved over a period a time with real-time performance being a prime consideration. The resulting simulator frame rate is approximately 300Hz. The FCS Fortran definition code is simply compiled and executed with the appropriate interfaces to the aerodynamic model, and at the defined iteration rates.

B.5.4 Validation.

Cross checking with the off-line equivalent model is the primary method of validating the simulator. Both the off-line and real-time facilities use different software and different versions of the same aerodynamic data set and, when a cross-check match is achieved, it also provides an additional level of confidence in the validity of both models.

The steps in the validation process are:

a) Static checks of aerodynamic model. The model is forced to a particular flight condition (airspeed, altitude, incidence, sideslip, g, mass, centre of gravity etc.) and the aerodynamic force and moment coefficients are extracted. The software used for this is as close to the run-time standard as possible.

b) Static checks of the FCS model. Given a fixed set of sensor and control demand conditions, the values at various points within the FCS software network are extracted and cross checked.

c) Dynamic checks of aerodynamic model. The unaugmented aerodynamic model is forced by known inputs to the control surfaces and a time history produced. In the case of a relaxed stability aircraft such as EAP this has limited application in the pitch axis because of its rapid divergence but is a useful cross check for the remaining stable axes. Again, the checks are made at different flight conditions.

d) The final end-to-end check is made by forcing the complete FCS and aerodynamics model with known pilot control displacements. As before, time histories are produced for various flight conditions. It is important to consider combined controls as well as single axis inputs.

B.5.5 FCS Developments.

The simulator model validated as above is used to allow pilot-in-the loop assessments as part of the design process. Deficiencies or recommendations are reported back to the designers who may offer a revised FCS. This is implemented using the same processes, and re-assessments then take place. Design iterations are carried out in this way until a satisfactory standard of FCS is achieved. Any refinements in aerodynamic data are introduced as necessary, again using the same validation methods. At this stage, FCS design can be considered to be complete.

B.5.6 FCS Clearance.

Detailed assessments are carried out through a fine matrix of flight conditions, up to and beyond the limits of the flight envelope, using both the design dataset and data subjected to tolerances. These are confidence checks to ensure that the FCS design is robust within its flight envelope. Beyond the envelope, the handling should degrade gracefully without 'knife-edge' situations developing. Applying tolerances to the data is an additional confidence check, which ensures that the sensitivity of the FCS performance to design data accuracy is what was anticipated.

B.5.7 Pilot Familiarisation.

Lastly, the simulator is used for pilot familiarisation. This is not training as such but reminding the aircrew of the expected aircraft handling prior to flight. In the case of a completely new configuration such as EAP, the complete first flight schedule was rehearsed on the simulator.

As the above discussion indicates, the man-in-the-loop simulator plays a vital role in the various stages of the design, development and clearance of an FCS for an aircraft such as EAP. It is however a facility which is one part of a larger set which includes off-line models as well as test rigs. The underlying theme throughout the process is the build up of confidence in both the aircraft handling qualities and the facilities used to design those handling qualities.

B.6 GRUMMAN F-14A AUTOMATIC RUDDER INTERCONNECT (ARI) TESTING

The Naval Air Development Center has developed, validated and refined the centrifuge-based Dynamic Flight Simulator (DFS) to simulate the total G-force environment of high-performance military aircraft. The DFS is the only simulator in the world capable of producing the pilot-controlled, sustained, high-G environment experienced in actual air combat maneuvering engagements. It utilizes a 50 foot radius, man-rated centrifuge as its moving base. This simulator, with its dual-gimballed gondola, can provide linear accelerations in any of three mutually perpendicular axes (Gx, Gy, and Gz) up to a magnitude of 10 G with onset rates as high as 3-5 G/sec. The DFS has been used to study:

1) the debilitating and disorienting environment imposed on a pilot during out-of-control and spinning flight regimes,
2) generic high angle of attack stability and control,
3) pilots' physiological response to high G eyeballs out spin maneuvers, and
4) advanced tactical aircraft control configurations.

Its aerodynamic and control system models and cockpit configuration can be readily modified to study handling qualities, control law authority, cockpit displays, and the effects of acceleration on pilot workload and performance. The DFS provides a means to safely address design concepts on the ground prior to flight testing.

The baseline DFS F-14A application program included the original NASA-Langley Automatic Rudder Interconnect (ARI) control system. The U.S. Navy, in conjunction with Grumman and NASA Dryden, have been developing and flight testing a new Low Speed Cross Control ARI (ARI/LSXC). This new ARI is similar to, but different from that used in the original F-14 application. The system includes:

- Slow speed (Mach less than 0.4) feedforward loops
- Gain and breakpoint changes
- Cross control logic
- A Deadband in the ARI yaw rate feedback terms
- Variable gain control capability (for test purposes only).

The original ARI code was updated to reflect these new capabilities. The Variable Gain Control switch settings and an ARI ON/OFF switch were implemented to provide the experimenter with control of the ARI.

The implemented ARI consists of 5 basic elements: (1) automatic differential stabilizer limiting; (2) automatic spin prevention; (3) lateral stick to rudder interconnect; (4) wing-rock suppression, and (5) low speed/high angle of attack (AOA) cross control capability. Elements (1) and (2) are designed to improve the departure/spin resistance of the F-14. Elements (3) and (4) are primarily high AOA flying qualities enhancement features. Element (5) was specifically designed to provide the pilot with increased roll/yaw maneuvering capability in the low speed/high AOA flight regime.

Validation of the resulting ARI modifications was conducted via both batch and real-time testing. The batch tests consisted of functional tests to investigate the DFS Automatic Rudder Interconnect implementation versus the control system block diagrams. Following successful completion of the batch tests, real-time tests were conducted to investigate the simulated aircraft's response to control system commands at high angle of attack.

The batch tests were conducted from a trim condition of 0.5 Mach at 30,000 feet altitude, with all Stability Augmentation Systems (SAS) and ARI ON. Full lateral stick was selected to command a roll, followed by smooth aft longitudinal stick application, while maintaining the lateral stick input, to increase angle of attack. Commanded control surface positions were then recorded as a function of angle of attack and plotted against the control system design parameters. The low speed cross control logic was tested from a similar trim condition. In this case, rudder pedal was applied opposite to lateral stick in an effort to induce a more rapid roll. Longitudinal stick was then applied to increase the angle of attack. Again, the differential tail and rudder deflections followed the ARI schedules with angle of attack until the cross control thresholds were satisfied. With angle of attack greater than 30 degrees and Mach number less than 0.4, the cross control logic restored full commanded surface deflections. Excellent agreement between the recorded data and the control system design parameters was obtained, thereby validating the functional operation of the simulated ARI.

The Variable Gain Control feature was also validated during both batch and real-time testing. It was used to isolate individual loops of the control system during software unit testing and verification, as well as to modify control gains in response to on-going flight test development.

Satisfactory implementation of the DFS simulated F-14 ARI provided the NAVAIRDEVCEN with additional capability to support development of the F-14's fight control system in a safe, efficient manner under realistic sustained-g maneuvering conditions prior to a flight test.

B.7 HIGH AGILITY FIGHTER AIRCRAFT - X-31

The advent of all-aspect capability air-to-air weapons is causing changes in the air combat maneuvering doctrines of tactical fighter aircraft. These new weapons - including radar controlled guns in combination with pointing flight modes - provide improvements in air combat capability via improved energy maneuverability. New maneuver modes are required to provide the pilot with substantial improvements in close-in combat effectiveness. One such mode involves Post Stall Maneuvering (PST).

The U.S. Defense Advanced Research Projects Agency (DARPA) in conjunction with the U.S. Navy and the West German government has developed a prototype aircraft designated the X-31 whose mission is to investigate the technology of post-stall (PST) maneuvering and enhanced fighter maneuverability (EFM). PST/EFM entails flight at high angles of attack, beyond aerodynamic stall, in which the aircraft is rotated about the wind vector through the use of thrust vector control. Such a maneuver enables the pilot to gain a tactical advantage over an adversary by pointing his aircraft to acquire a firing opportunity more rapidly than can his opponent.

The NAVAIRDEVCEN participated in an EFM flight simulation program using its Dynamic Flight Simulator (DFS). The program's purpose was two-fold: (1) to assess the DFS's ability to duplicate the unusual disorienting aspects of the PST environment and (2) to perform basic human factors experiments concerning EFM control/display concepts.

Specific areas of concern in this simulation included: (1) the effect of sustained G, G-onset rates, angular accelerations and acceleration rates on the pilot/aircraft combination, (2) the need for special PST displays, and (3) trade-offs in control laws and control system mechanization.

The flight control laws in the DFS EFM simulation went through a number of revisions during this program. Modifications were added to the physical characteristics of the cockpit controls, the control functions and the flight control laws themselves. These modifications were accomplished to provide the pilots with the ability to evaluate alternative means of conducting the PST maneuver (i.e., use of lateral stick and/or rudder pedals) to provide a thrust vectoring capability for control at high angles of attack to reduce their workload in executing the PST, and to improve their performance in the PST.

Execution of the PST maneuver in the DFS EFM aircraft required the utilization of pitch vanes to establish and maintain the extremely nose high attitudes, and yaw vanes to turn the simulated aircraft at high angles of attack. The pitch vanes were controlled via the longitudinal stick as a function of stick position aft of the stick detent position. The yaw vane was implemented via either the rudder pedals or the lateral stick. The DFS crewstation was modified to provide both angle of sideslip and angle of attack indicators to improve the pilot's ability to control the airplane at high angles of attack.

Based on the results of this study, the DFS was found to be a unique laboratory for the study of high agility aircraft. The simulated post stall maneuvers were consistent and repeatable and induced no gross ill effects based on linear or angular accelerations. New approaches to cockpit controls and displays for this class of aircraft were successfully evaluated to determine their value in improving the pilot's attitude awareness and performance.

Appendix C

SOFTWARE CONFIGURATION MANAGEMENT

Configuration control procedures should be defined in a Configuration Management Plan. This plan should define personnel and organisational responsibilities, configuration management strategy and scope, and operational procedures (including support tools). The international standard ISO 9000 provides further guidance.

In general, the operational procedures should embody the following features. However, some of the features identified below are regarded as desirable rather than essential (denoted by *) and may not be readily supported by proprietary software management tools for specific applications, eg due to programming language or system characteristics.

a) File management.

1. Each file should have a unique name and a designated owner (a person).
2. Files (source, 'include' and object) should be renamed or copied to a protected directory (by an authorised user).
3. The protected directory should be backed up regularly, and the identifiers of the off-line storage media used should be recorded.
4. Files should have the option of password protection.
5. Files in the protected directory should be read-only accessible to all users (using password if appropriate).

* 6. File dependencies should be formally identified.

b) Configuration definition

1. Each configuration definition should have a designated owner.
2. A configuration definition should itself be subject to configuration management in the same way that files are managed.
3. It should be possible for any file, at a specified version, to be included in any configuration.

c) Version identification

1. All files and configuration definitions should employ a clear, structured version numbering scheme.
2. The identification scheme should identify the file or configuration's state, ie baseline or under development/not tested.

d) Change control

1. Each change specification should have a unique identifier and a designated owner (the person who is authorised to refine the change specification and responsible for the work).
2. Each change specification should clearly state the reason for the change and the files or configuration definitions affected.
3. Each change specification should be stored in a protected area.
4. All users affected by a proposed change should indicate their agreement with the change specification before it is actioned.
5. Once the change specification is agreed, it should not be modified further.
6. Parallel changes to the same file or configuration definition should not be allowed.
7. An authorised, independent user should approve the implementation of the change before the file or configuration definition is re-baselined. The approval details should be logged in a protected area.
8. The date and change identifier should be recorded for each version of a file or configuration definition.

* 9. It should be possible to log software problems for which change specifications will be raised in the future.

e) Development support.

* 1. When a file is modified, all the files that depend on that one should be automatically updated.

* 2. Pre-processors, compilers, linkers, utilities, etc. should be automatically invoked.

* 3. The specified file dependencies should define the order in which the files are automatically processed.

* 4. Default processing options should be automatically specified for the files in a given configuration.

REPORT DOCUMENTATION PAGE

1. Recipient's Reference	**2. Originator's Reference** AGARD-AR-278	**3. Further Reference** ISBN 92-835-0757-6	**4. Security Classification of Document** UNCLASSIFIED/ UNLIMITED

5. Originator
Advisory Group for Aerospace Research and Development
North Atlantic Treaty Organization
7 rue Ancelle, 92200 Neuilly sur Seine, France

6. Title
AIRCRAFT AND SUB-SYSTEM CERTIFICATION BY PILOTED SIMULATION

7. Presented on

8. Author(s)/Editor(s) Various	**9. Date** September 1994
10. Author(s)/Editor's Address Various	**11. Pages** 54

12. Distribution Statement
There are no restrictions on the distribution of this document. Information about the availability of this and other AGARD unclassified publications is given on the back cover.

13. Keywords/Descriptors

Flight simulation
Validation methods
Certification
Qualification
Pilot interaction

14. Abstract

There is a steadily increasing tendency to use piloted flight simulators for official clearance of selected areas of flight envelopes and of system behaviour or malfunctions. This is a natural and desirable evolution from the wide use of simulation during the development of new aircraft. However there is a lack of guidance for certification authorities and aircraft manufacturers on simulation standards, validation procedures and general information on the advantages and disadvantages of using simulation as part of a clearance programme. This could lead to either inappropriate use of simulators, or unnecessary (and costly) reluctance to use simulation when it is appropriate. In particular, there is concern by many involved with research and engineering development simulators that subjective pilot opinion is often the primary criterion for acceptance of simulators for certification activities. However, clearance demonstrations on a simulator will not usually be experienced in flight until an operational pilot encounters the conditions or configurations of the clearance. Thus validation of the simulator for clearance tasks must involve rigorous model and simulation system validation as well as pilot subjective tests. Subjective adjustments are unacceptable.

Working Group 16 was formed by the Flight Mechanics Panel of AGARD to produce a Report on this subject. The aim was to provide advice and guidance to Certification and Acceptance Authorities, and Aircraft Manufacturers on the appropriate use of piloted simulation as the sole demonstration for aircraft and system flight clearances.

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AGARD Advisory Report 278
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ISBN 92-835-0757-6

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ISBN 92-835-0757-6

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ISBN 92-835-0757-6